Research on comprehensive evaluation model of rural domestic sewage treatment technology based on fuzzy comprehensive evaluation and analytic hierarchy process method

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Abstract

In China, rural domestic sewage treatment has become an urgent problem to be solved to improve the rural human settlement environment. However, there is no scientific, objective, and systematic evaluation model for selecting rural domestic sewage treatment technology. Therefore, this paper mainly studies on the establishment of the evaluation system model for China's typical rural domestic sewage treatment technology and the application of technology selection. Based on the analytic hierarchy process and the life cycle method, the experts consulted and analyzed the factors affecting the evaluation of China's rural sewage treatment technology. The comprehensive evaluation index system suitable for China's rural sewage treatment technology was established based on the analysis results. Combined with the fuzzy comprehensive evaluation method, five typical rural domestic sewage treatment technologies were applied and analyzed. The results show that the comprehensive evaluation of the biofilm technology is best at 3.5669, followed by the septic tank treatment technology and land treatment technology, which are 2.8829 and 2.8422, respectively. The case analysis verifies the applicability of the model, which can support the selection of technologies for the rural domestic sewage treatment market in China.

Key words: analytic hierarchy process, fuzzy comprehensive evaluation, life cycle assessment, rural domestic sewage treatment technology

Highlights

- Summarizes the water ecological environment in rural China.
- Summarizes the application of rural sewage treatment technology in China.
- Propose a model for rural domestic sewage treatment technology.
- Select typical technology for empirical analysis.
- Based on the analysis results, put forward constructive opinions on the status of rural sewage treatment technology in China.

INTRODUCTION

China's rural population base is enormous. According to the demographic data released by the National Bureau of Statistics in 2017, the rural population in China is 576.1 million, accounting

for 41.48% of the total population (Wang *et al.* 2018). China's rural domestic sewage accounts for about 1/2 of the national domestic sewage discharge, and only a few villages have sewage discharge pipe networks or sewage treatment facilities. Most of the villages' domestic sewage is discharged into nearby rivers and lakes at will, which has caused great pollution to the rural living environment (Shen *et al.* 2014). The innovation of sanitary ware and the popularization of tap water have led to a sharp increase in the discharge of rural domestic sewage. In 2016, China's rural sewage treatment rate was less than 22%, and sewage discharge reached 20.2 billion tons and is expected to reach 30 billion tons by 2020, with huge sewage discharge. China's rural domestic sewage has obvious characteristics such as wide coverage, dispersion, multiple sources, rapid growth, and low treatment rate (Tao & Zuo 2009). At present, the key issue that urgently needs to be solved in rural domestic sewage is to select appropriate technology for harmless treatment and resource utilization of rural domestic sewage.

Rural domestic sewage includes domestic washing sewage, kitchen and toilet flushing sewage, livestock, and poultry sewage. Since the 1990s, China has gradually researched rural domestic sewage treatment technology and carried out the construction of rural sewage treatment demonstration projects following rural areas' actual conditions in different regions (Zeng 2001). In densely populated areas, water quality, water quantity, and regional environment are the keys to rural domestic sewage treatment (Tan *et al.* 2011). The quality of rural domestic sewage has a single composition and small fluctuations. Its COD and BOD_5 concentration ranges are generally 350–770 mg/L and 200–400 mg/L, with good biodegradability, and its indicators such as SS, TP, TN, and pH are less different from urban domestic sewage (Chen 2020).

Many rural sewage treatment technologies are applied at home and abroad, divided into three methods: physical methods, chemical methods, and biological methods according to the principle of action. Physical methods include gravity, centrifugation, filtration, and so on; chemical methods include coagulation, adsorption, electrolysis, and so on; biological methods include activated sludge and biofilm methods, and so on (Zhu *et al.* 2020). According to the main technical unit composition classification, it is mainly divided into three types: biological treatment technology, ecological treatment technology, and combined treatment technology. The 119 rural domestic sewage engineering cases that can be verified from 2000 to 2016 can be classified into three technical modes: biological treatment, ecological treatment, and combined treatment, accounting for 5.88%, 14.29%, and 79.83%, respectively.

The purification of rural domestic sewage by biological treatment technology mainly relies on the metabolism of microorganisms. The technology uses less land area, produces less sludge, and has a strong impact load capacity. It has a good treatment effect on rural sewage with large water quality fluctuations and volume (Ma & Yi 2019). The composite biological filter process developed by Li *et al.* (Li 2018) can combine the characteristics of front and rear denitrification, and has the advantages of low energy consumption, simple operation, and maintenance, and not easy to be blocked. The effluent reaches the first-level A standard. Ecological treatment technology is a sewage treatment technology that uses a series of physical, chemical, and biological effects produced by microorganisms, soil, animals, and plants to degrade pollutants in rural sewage (Liu *et al.* 2018). Rivas *et al.* (2011) connected a vertical flow constructed wetland and a horizontal flow constructed wetland in Mexico and achieved good effluent quality through the combined flow's reflux operation. Bioecological combination technology is the combination of biological treatment technology and ecological treatment technology. The pre-biological treatment uses microorganisms to remove organic matter effectively, as well as some nutrients. The latter part of the ecological treatment is further dephosphorization and denitrification, complementary advantages, further improving and ensuring the stability of the effluent quality (Chang 2018). Shi *et al.* (2016) combined an anaerobic biological filter with a constructed wetland to treat rural domestic sewage; the combined process has no power consumption, low cost, easy operation, convenient management, and protection.

Among the ecological treatment technologies, the proportions of constructed wetlands, oxidation ponds, and land infiltration processes were 72.22%, 11.11%, and 16.67%, respectively. Among the

combined treatment technologies, the biological plus ecological treatment combination accounted for the largest proportion, accounting for 71.28%, and the biological plus biological and ecological plus ecological treatment combinations accounted for 19.15% and 9.57%, respectively. In the 105 related documents investigated, we found a fascinating phenomenon: 74 literatures all indicate the effluent discharge standard, accounting for 70.48%. This shows that in the current practice of rural domestic sewage treatment technology, the researcher's focus is mainly on pollution treatment technology, which is related to the late start of rural domestic sewage treatment in China.

There are many kinds of technologies for rural domestic sewage treatment. When choosing the applicability of the technology itself, factors such as economy, management, and environment must be considered. Nevertheless, few researchers focus on the comprehensive evaluation of the cost and output of rural domestic sewage treatment technology. Based on the above research background, this paper focuses on China's rural sewage treatment's genuine and critical concerns. A comprehensive evaluation based on the analytic hierarchy process (AHP) and life cycle assessment (LCA) are constructed based on many literature surveys, field surveys, and relevant expert guidance with engineering experience. The model evaluates China's typical rural sewage treatment technology and provides a direct theoretical basis for selecting China's rural sewage treatment technology. Through the evaluation results of the fuzzy comprehensive evaluation model, the advantages and disadvantages of various rural domestic sewage treatment technologies are analyzed, and policy recommendations for the development planning of rural domestic sewage treatment technologies are put forward.

The remainder of the paper is organized as follows. Literature review reviews relevant literature on the evaluation mechanism and methods of sewage treatment technology. Methodology introduces data definitions and provides methodologies of establishing a comprehensive evaluation index and model. Empirical results and discussion describes the comprehensive evaluation results and reason analysis of the typical rural domestic sewage treatment technologies that have been piloted in rural areas.

Literature review

A wealth of literature has raised the discussion about the comprehensive evaluation of sewage treatment technology. In the aspect of the index system, research on sewage treatment technology, the environmental protection industry is a hot topic. In recent years, sewage treatment workers in China have conducted many comprehensive evaluation studies on sewage treatment projects, and have put forward many evaluation index systems. Research on the evaluation of sewage treatment technology by scholars at home and abroad began in the 1980s. With the in-depth study of multi-objective decision-making methods, the evaluation system has gradually transitioned from single economic target evaluation to multi-objective comprehensive evaluation of economy, technology and environment. The ultimate goal is to enable the sewage treatment technology to achieve the rational allocation of energy and resources, and to optimize the social, economic, and environmental benefits (Wang & Lou 2004). The sewage treatment technology evaluation research has mainly experienced the stages of cost model research, benefits evaluation index model research, grey system research, and analytic hierarchy process research.

Among the existing studies, Yin and Zhang established the dynamic total construction cost, civil construction cost, piping cost, and equipment cost function by mathematical statistics based on the relevant data on the processing structure of each unit of the domestic sewage treatment plant in 1982 (Yin & Zhang 1990). The model lacks a systematic viewpoint, the trial algorithm used in the calculation is quite different from the actual situation, and the cost function obtained is the same. Therefore, the cost model has certain limitations in the comprehensive evaluation and application of urban sewage treatment technology.

Given the shortcomings of the cost model research, He *et al.* proposed the benefit evaluation index model (He 1989). The model establishes a basic framework for a comprehensive evaluation of urban

sewage treatment technology. However, the evaluation index range of this model is relatively narrow, and the selected indexes only include some deterministic impact factors (operation rate, removal rate, and compliance rate of facilities in the operation management indexes). The impact factors of other uncertainties such as resource utilization and secondary pollution have not been considered, so the evaluation results differ significantly from the actual situation.

After the 1990s, Chinese researchers began to use multi-objective decision-making methods in the comprehensive evaluation of urban sewage treatment technology, not from a single economic point of view. Mu and Li established the index system for the evaluation of the practical effect of a cooking waste liquid treatment project in a small straw pulp mill by consulting relevant experts and using the method of fuzzy closeness (Mu & Li 1997). Their result was only to establish an index system, without applying evaluation methods, to conduct comprehensive evaluation and ranking of the enterprises under investigation. Afterwards, Zhang and Wang established an index system with eight indexes and evaluated the performance of the sewage treatment plant using the grey optimal order method (Zhang & Wang 1993). This method also has some shortcomings, such as the selection of impact factors for the selection of evaluation indicators and the unclear level of the indicators. In mathematical operations, the initial data lacks reliability, which affects the subsequent evaluation results.

In response to the above problems, many domestic scholars have introduced fuzzy mathematics theory to improve the grey correlation method further. Ling proposed the grey relation fuzzy decision method and grey relation model, respectively, for the evaluation of urban sewage treatment technology (Ling 1998). On the one hand, the reliability of the initial data is improved; on the other hand, critical influencing factors are emphasized. Nevertheless, in the evaluation indicators, there are still some shortcomings such as the selection of influencing factors and the unclear levels, so that the calculation results of the weight cannot objectively reflect the degree of influence of each indicator.

In allusion to the complexity of multi-factors in the evaluation system of urban sewage treatment technology, Jiang *et al.* proposed a multi-level fuzzy grey coupling model based on the multi-level fuzzy comprehensive evaluation model proposed by Li (Li 2000). In this model, the multi-level hierarchical evaluation index system established according to the analytic hierarchy process tends to be perfect, and the index level is apparent. Regrettably, the selection of evaluation indicators does not take into account factors such as resource utilization, environmental impact and local conditions.

It can be seen from the above that the objects of the traditional evaluation index system mainly evaluate the operation effect and performance of sewage treatment plants. Although there are also studies on the evaluation index system of sewage treatment technology, the established index system is not comprehensive, and there is a lack of relevant analysis of the established index system in conjunction with the evaluation objectives. Therefore, the results obtained by using different evaluation index systems and different evaluation methods vary greatly. Besides, the research on the evaluation index system of China's rural domestic sewage treatment technology is still a blank. According to Science Direct, there are up to 40,000 papers with the title 'evaluation of sewage treatment technology', but the number of documents related to the evaluation of rural domestic sewage treatment technology is minimal. Papers with titles containing an evaluation of rural domestic sewage treatment technology are not searchable, and there are less than 3,000 papers related to the evaluation of rural domestic sewage treatment technology. The research on the evaluation of rural domestic sewage treatment technology is insufficient.

This study conducts a comprehensive evaluation of rural domestic sewage treatment technology. Firstly, we screened out high correlation index and built a comprehensive evaluation index system of rural domestic sewage treatment technology, which is based on AHP combined with experts' authority level to determine the index weight. Then the qualitative and quantitative indicators are classified. Finally, a fuzzy hierarchy comprehensive evaluation model is established to evaluate the superiority of the rural domestic sewage treatment technology. The technology roadmap is shown in Figure 1.
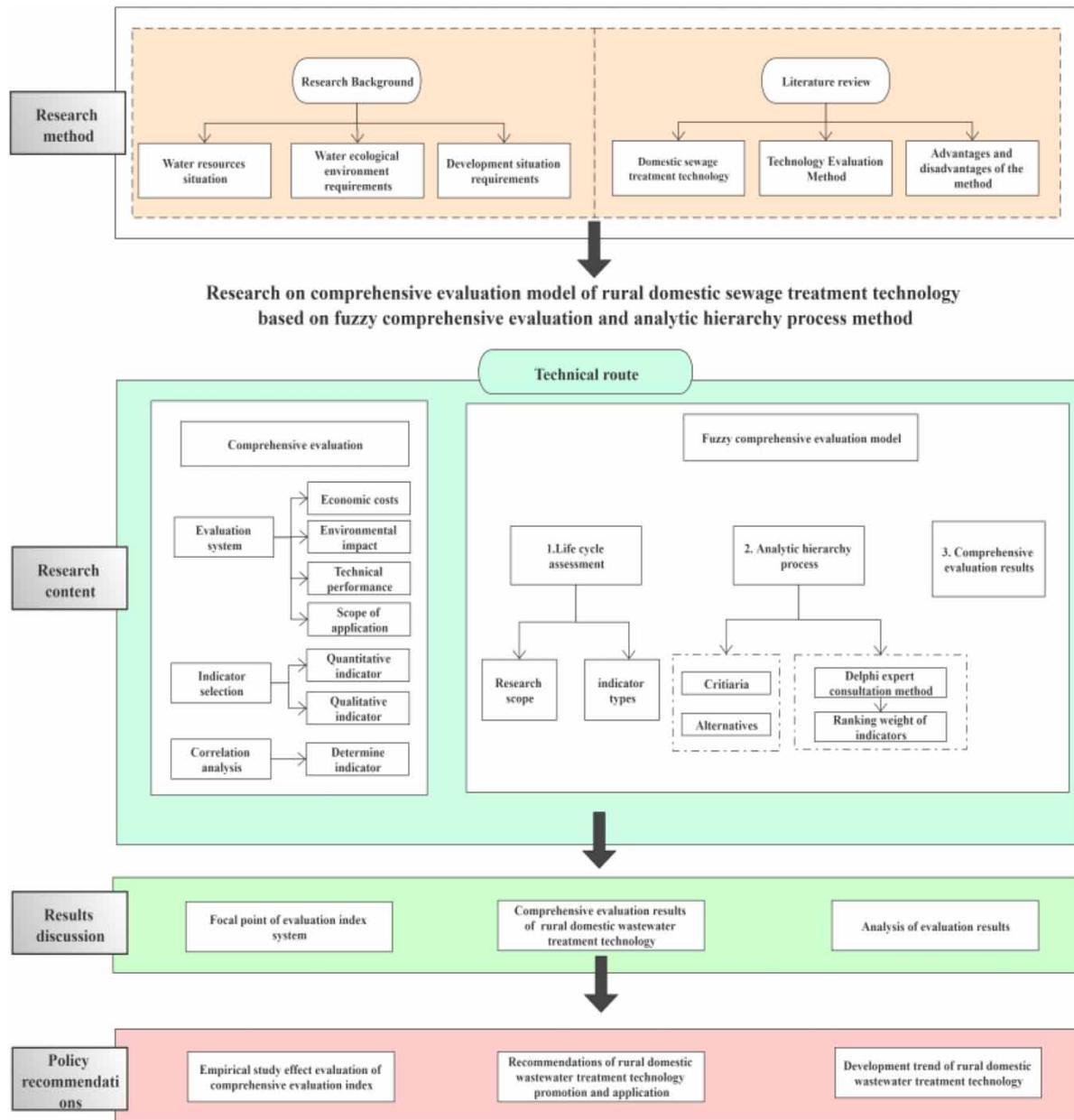
Figure 1 | Comprehensive evaluation technology roadmap of rural domestic sewage treatment technology.

METHODOLOGY

This paper mainly determines the ranking by determining the weight of each indicator and the score of each indicator for each technology, and then calculating the total score. The specific calculation logic is as follows:

(1) Determine the evaluation objective.
(2) Through the LCA method, with the idea of 'divide and conquer', the decision goals are decomposed to form criteria and evaluation indicators, and finally construct a hierarchical model.
(3) Use this hierarchical model to generate an AHP questionnaire and invite experts to participate in the survey.
(4) Collect the AHP questionnaires of the experts to get the ranking weight of each evaluation index to the evaluation target. At this point, the AHP process is completed.

(5) Use the evaluation indicators of the hierarchical model; that is, the elements of the plan layer, as the evaluation factors to generate the FCE questionnaire.

(6) For each evaluation objective, find experts/evaluators to fill in the FCE questionnaire.

(7) Collect the fuzzy comprehensive evaluation questionnaire, sort the weights (as the weight vector of FCE) based on expert data and various evaluation factors obtained by AHP, and calculate the comprehensive evaluation results of each evaluation target.

Life cycle assessment

A sewage treatment system can reduce the concentration of pollutants in raw water during operation. However, the sewage treatment facility will consume resources, energy and discharge pollutants to the environment during its life cycle from construction to operation. In the past, the traditional evaluation methods for sewage treatment technology mostly considered the treatment efficiency and economic benefits of the technology, but did not consider the environmental benefits, and ignored the direct and indirect environmental emissions of sewage treatment facilities during construction and operation. The life cycle assessment method is a tool for assessing the environmental load of the research object, which is generally recognized internationally.

The choice of rural domestic sewage treatment technology will inevitably bring about a wide range of impacts, including economic investment, environmental issues, social issues, and so on. The establishment of the evaluation system is the basis of scientific evaluation. The basic principles of establishing a rural domestic sewage treatment technology index system include completeness, independence, flexibility, simplicity, operability, dynamics, and sustainability. In the actual analysis, it is necessary to comprehensively consider all the principles and analyze the organic combination of technical subjects and technical needs.

In order to avoid an incomplete evaluation system caused by the omission of indicators, the rural domestic sewage treatment technology is taken as the research object, the full life cycle range of technology from production and use to scrapping is clarified, and a relatively comprehensive indicator system is determined through full life cycle cost analysis. The complete life cycle of rural domestic sewage treatment technology should cover the entire process from technology generation and operation to technology elimination, from collecting equipment materials, making equipment, making sewage treatment facilities, system operation and maintenance, to equipment disposal. Figure 2 shows the research scope and indicator types for determining the life cycle of rural domestic sewage treatment technology.
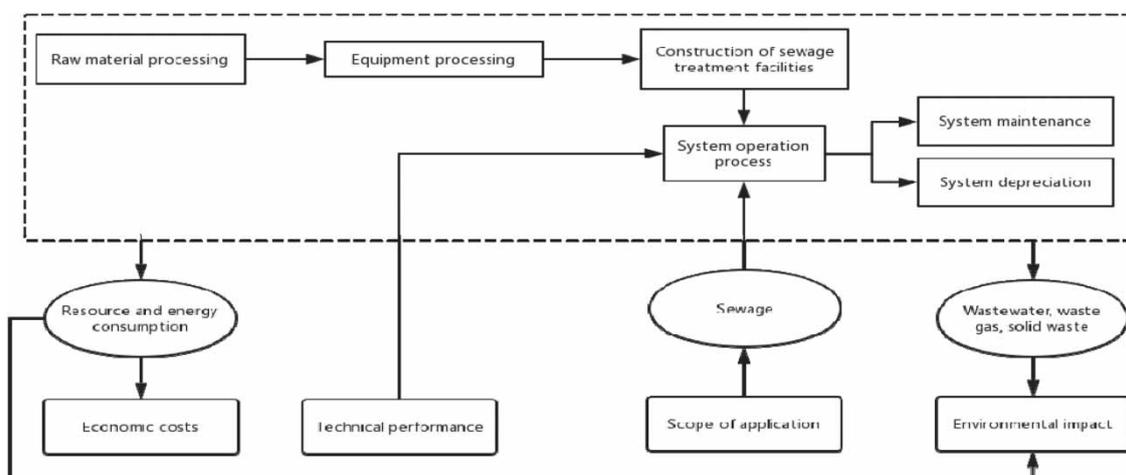
Figure 2 | Rural domestic sewage treatment technology life cycle research scope.

The theoretical basis of the monetization method is that the importance of each environmental impact category can be measured by currency. In the system, market prices are generally used. If the market price cannot be obtained, other indirect methods are used to obtain value, such as the willingness evaluation method and the hedonic value method (Nguyena *et al.* 2016). However, such mixed use of various methods can easily lead to uncertainty in the value. As mentioned earlier, the willingness to pay method is the basis of the monetization method. When assessing environmental impacts, social willingness to pay is generally used. Environmental taxes for environmental polluters and resource extractors are a typical social willingness to pay. After careful consideration, this paper decided to use the monetization method to determine the weight system of environmental impact.

The rural domestic sewage treatment technology is selected as one cycle to compare and analyze. According to the type indicators and equivalent indicator units of various environmental impact types issued by the authority of the standards organization, the basic steps of environmental impact analysis in ISO14042 were classified, characterized and weighted according to the environmental management life cycle assessment. The environmental impact of various factors was evaluated, converted inventory data into environmental impact parameters, and used the equivalent factors of various environmental disturbances to standardize and compare the analysis.

The weight of an environmental impact type should be the weighted average of the environmental tax limits of several typical pollutants, and the weighted average weight of a certain environmental impact type is defined as in Equation (1).

$$w_i = \sum_j (e_{ij} \cdot c_{ij}) \quad (i, j = 1, 2, 3 \ldots) \tag{1}$$

In the formula:

w_i- Weight of an environment type;

c_i- Monetary factor; that is, the environmental tax value of the j-th pollutant of the i-th environmental factor, for the sake of unification, its unit of measurement is converted into an environmental impact equivalent;

E_{ij}- The potential impact coefficient is related to the pollutant's pollution capacity and total emissions. In order to simplify the calculation, only the typical impact factors (typical pollutants) of each environmental impact type are selected, such as global warming, only CO_2 and CH_4 are used as indicators for calculation.

The calculation method of the influence potential coefficient is shown in Equation (2).

$$e_{ij} = \frac{f_j \cdot a_j}{\sum_j (f_j \cdot a_j)} \quad (i, j = 1, 2, 3 \ldots) \tag{2}$$

In the formula:

F_j- Impact potential per unit of pollutant;

A_j- The average annual emissions of pollutants (from the average emissions in 2013, 2014 and 2015).

It should be noted that the allocation of four indicators in the environmental impact indicators adopts the idea of the monetization method in LCA for weight allocation, and the remaining indicator weights are determined by the AHP method.

Comprehensive index construction

(1) Selection of evaluation index

Based on the enterprise investigation and expert consultation, combining quantitative and qualitative index, we select economic cost, environmental impact, the scope of application and technical performance as proxies for the first-level indicators (Table 3). After that, the 17 secondary-level indicators, such as global warming are selected.

(2) Correlation analysis of evaluation index

Correlation analysis is used to quantify the association between two continuous variables. In correlation analysis, we estimate a sample correlation coefficient to determine the correlation degree and direction between variables. In this study, we establish a comprehensive evaluation index system of rural domestic sewage treatment technology. Since qualitative indicators cannot be as accurate as the quantitative index, they are not suitable to analyze data characteristics. Therefore, we only apply correlation analysis to quantitative indicators.

Analytic hierarchy process

The AHP framework is a popular tool for formulating and analyzing decisions, which is extremely useful for ranking alternatives, as well as calculating the weights of different criteria through pairwise comparisons (Meng *et al.* 2012). AHP establishes a balance between quantitative and qualitative factors, as it makes it possible to incorporate judgments on intangible qualitative criteria alongside tangible quantitative criteria. The AHP method is based on three basic rules/factors: first, the structure of the model; second, comparative judgment of the alternatives and the criteria; third, synthesis of the priorities. Based on the above, it is clear that AHP has two main advantages: mathematical simplicity and flexibility. These two are probably the reasons why AHP is a favorite research tool in many fields, including energy management and renewable energy sources. The specific analysis steps are as follows.

(1) Construct a pair-wise comparison matrix

The significant advantage of the AHP method is that, instead of asking experts to give a weight for a particular evaluation factor directly, experts will be asked to rate the relative importance of the different factors. Saaty proposes a linear scale for assigning comparison values to a_{ij}, and has been widely used (Saaty & Vargas 1998). Table 1 presents Saaty's scale of preferences in the pair-wise comparison process. Usually, the numbers of judgments needed in the upper-right triangle of the matrix are $n(n-1)/2$, where n is the size of the matrix.

(2) Calculate the maximum eigenvalue and corresponding characteristics of the judgement matrix

Table 1 | Saaty's lineal scale of preferences in the pair-wise comparison process

Numerical rating	Judgments of preferences between factor *i* and *j* rating
1	Factor *i* is equally important to factor *j*
3	Factor *i* is slightly more important than factor *j*
5	Factor *i* is clearly more important than factor *j*
7	Factor *i* is strongly more important than factor *j*
9	Factor *i* is extremely more important than factor *j*
2, 4, 6, 8	Intermediate values

In this study, the eigenvector (after normalization) is the weight vector w_i, and the calculation formula is as in Equation (3).

$$w_i = \frac{\sqrt[n]{\prod\limits_{i=1}^{n} \alpha_{ij}}}{\sum\limits_{i=1}^{n} \sqrt[n]{\prod\limits_{i=1}^{n} \alpha_{ij}}} \tag{3}$$

(3) Consistency check

Because the comparison results will be inconsistent after the paired comparison is integrated, scholars generally believe that inconsistencies are allowed within a certain range, so it is necessary to test the consistency of the judgment results. The consistency ratio is calculated according to the definition of T L Saaty, such as in Equation (4).

$$CR = \frac{CI}{RI} \tag{4}$$

where RI is the average random index, which is computed and tabulated, as shown in Table 2. CI is the consistency index, which can be calculated as:

$$CI = \frac{\lambda - n}{n - 1} \tag{5}$$

If a value of the consistency ratio CR is less than 0.1, the numerical judgements will be considered acceptable.

Table 2 | Random consistency index RI value

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Table 3 | Professional composition of expert advisory group

Research fields	Number of experts	Professional title
Technology consultation	4	Two senior engineer/Two engineer
Energy saving design	4	One senior engineer/Three engineer
Equipment supply	3	Two senior engineer/One engineer
Energy management	5	Two senior engineer/Three engineer
Users	9	Three senior engineer/Six engineer
Total	25	

Index parameter processing method

The core of this study is to obtain an intuitive and accurate evaluation model with broad applicability, and the evaluation of rural domestic sewage treatment technology is a multi-factor composite problem. Its indicators inevitably contain some qualitative indicators, such as those related to the

system. Indicators such as operational difficulty and matching conditions need to be effectively dealt with to ensure the consistency of quantitative and qualitative indicators.

(1) Systematization of qualitative index parameters

The systematization of qualitative index parameters is determined by the literature and relevant data and is assigned different importance scores of 1–9 respectively, and the relative coefficient is calculated using Equation (6), and then incorporated into the comprehensive evaluation system.

$$r_{ij} = \frac{x_{ij}}{5} \tag{6}$$

(2) Systematization of quantitative index parameters

The quantitative index parameters are divided into benefit type and cost type: the lower the cost type index, the better, and the higher the benefit type index parameter, the better. The efficiency index is standardized by the following Equation (7).

$$r_{ij} = \frac{x_{ij} - x_{i,\min}}{x_{i,max} - x_{i,\min}} \tag{7}$$

In the formula:

X_{ij}- Set the i-th index parameter of the j-th technology;

r_{ij}- Relative evaluation coefficient;

x_{max}, x_{min}- The statistics obtain the maximum and minimum values of the corresponding indexes in the evaluation object set.

The cost index is standardized using Equation (8).

$$r_{ij} = \frac{x_{i,\max} - x_{i,\min}}{x_{ij} - x_{i,\min}} \tag{8}$$

In the formula:

X_{ij}- Set the i-th index parameter of the j-th technology;

r_{ij}- Relative evaluation coefficient;

x_{max}, x_{min}- Obtain the maximum and minimum values of corresponding indicators in the evaluation target set by statistics.

Fuzzy comprehensive evaluation model based on AHP

Fuzzy logic, neural networks, and genetic algorithms were once hailed as the three significant algorithms of the 20th century with far-reaching influence. The 'approximate reasoning' of fuzzy logic is entirely different from the strict reasoning of binary logic. Fuzzy logic was created to allow computers to solve problems in a way close to human writing. The essence is that everything is related to the degree (Liu *et al.* 2017). The application object of fuzzy logic can include all decisions involving subjective, imprecise, or obscure information. Fuzzy control mainly consists of three necessary steps: fuzzification, fuzzy rules, and anti-fuzzification.

Fuzzy logic forms the basis of fuzzy expert systems, which can be used to deal with uncertainty and simulate common sense reasoning, which is often tricky for classical logic. The fundamental flaw of classical logic is its duality (Liu 2005). This limitation has advantages and disadvantages. The main advantage is that systems based on binary logic are easy to model so that the reasoning is accurate. The main disadvantage is that few things in the real world are genuinely binary. The real world is

complex, not a digital world. The value of fuzzy logic is not only a method of solving fuzzy information but more importantly, it has created a new research direction in the field of logic: the research direction of approximate reasoning logic. Fuzzy logic does not just help people solve practical problems containing 'fuzzy uncertainty' and 'fuzzy information', it provides an approximate solution method based on numerical calculation, because the column vector of the state transition matrix is the measurement result under different measurement conditions, Therefore, what fuzzy logic studies is the 'non-linear additive' problem of measurement results under different measurement conditions in high-dimensional space. Therefore, the fuzzy logic system can be used as an approximate verification system in various applications. In addition to the critical value of fuzzy logic in engineering fuzzy control, fuzzy logic also has extensive value in many fields. For example, the combination of fuzzy logic and computer makes the computer try to imitate the human brain's work. Similarly, the combination of fuzzy logic and management science and engineering has formed a colossal research group, such as investment decision-making, enterprise benefit evaluation, regional development planning, market forecasting, technology evaluation, and other fields.

The method used in this paper is a comprehensive fuzzy evaluation method based on fuzzy logic inference. Fuzzy multi-criteria methods constitute one approach to evaluate alternative decisions, which involve subjective judgments and are made by a group of experts. A pairwise comparison process is used to assist decision makers to make comparative judgments, while absolute judgments are made using a linguistic evaluation method. Fuzzy AHP overcomes the limitation of qualitative criteria, and solves the subjectivity, imprecision, and vagueness that are present in the decision problem, to formulate the uncertainties associated with perceptions and preferences (Rezaei & Ortt 2013). In the fuzzy AHP method, the evaluation index of the hierarchical model; that is, the element of the plan layer, is used as the evaluation index to generate the FCE (fuzzy comprehensive evaluation) questionnaire; for each tested object. Find experts/evaluators to fill out the FCE questionnaire; collect the FCE questionnaire, and rank the weights (as FCE weight vectors) based on the expert data and AHP's evaluation indicators, and calculate the comprehensive evaluation results of each tested object.

Technical options

Through literature surveys, nearly 150 rural domestic sewage treatment projects with a water treatment capacity of less than 1,000 $m^3 \cdot d^{-1}$ from 2000 to 2016 were collected. After screening, only 119 projects met the following two requirements: First, there was an explicit treatment water volume. The second is to have specific pollutant removal rate data or meet the emission standards. The relationship between the collection year of rural sewage treatment technology and the number of technologies is shown in Figure 3. It can be seen that the number of process cases changes in a wave-like manner with the year. This may be due to the incompleteness of the collection of process cases and the conditional restrictions on collecting literature cases. Nonetheless, it can still be seen that the literature on rural domestic sewage treatment technology from 2000 to 2016 has been increasing year by year, indicating that pollution control of rural domestic sewage has caused widespread concern among scholars.

According to past engineering practice, sewage treatment modes can be divided into centralized treatment and decentralized treatment. Centralized sewage treatment refers to establishing a large sewage treatment plant, a broader range of sewage unified collection and treatment, generally used in densely populated cities. For example, Tokyo, the largest city in Japan, ranks first globally in terms of population density. Tokyo's total urban sewage treatment capacity is 4.33 million m^3/d, divided into ten areas for centralized treatment based on sewer distribution, with an average size of 430,000 m^3/d per treatment plant. At present, centralized sewage treatment has evolved from localized, special sewage treatment to a systematic, large-scale sewage treatment model. Its advantages lie mainly in its effective control and water quality and quantity to maintain relative stability. However,
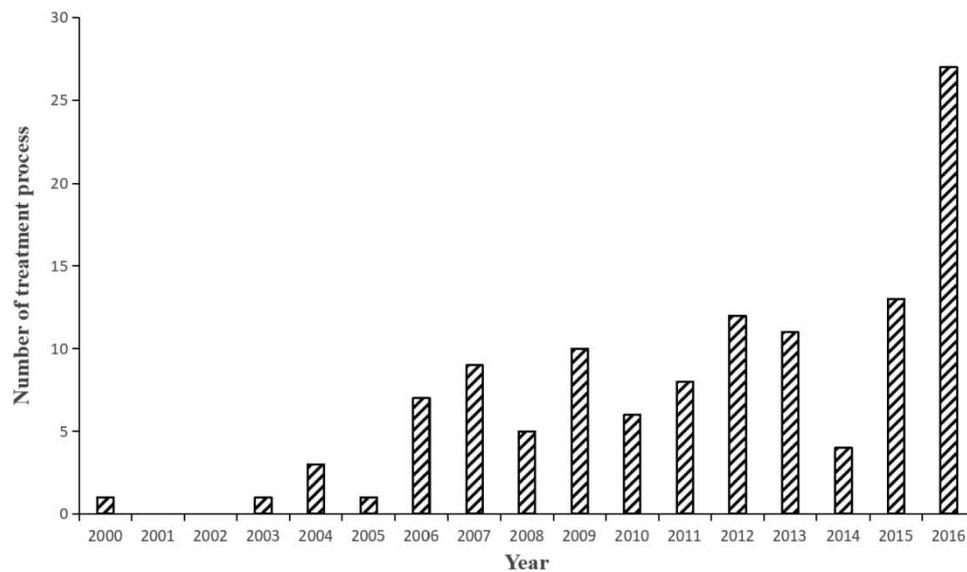
Figure 3 | Number of process types of rural domestic sewage treatment reported in different years.

its shortcomings are also pronounced: the initial investment is too high, and there is a need to deploy many pipe network systems and lift pumps.

The small size and low density of the population in the countryside's dispersed areas make it very unsuitable for the conventional centralized treatment mode. The countryside's primary industry is agricultural production, and decentralized treatment is very conducive to the recycling of useful resources in sewage waste. Therefore, it is advantageous to carry out a decentralized treatment model oriented towards resource utilization in rural areas of China, realizing the unity of social, economic, and environmental benefits and ensuring the sustainable development of rural ecology and economy. Given the actual situation in rural China, the technology evaluation object in this paper is also mainly decentralized treatment technology.

This study first analyzes a wide range of treatment options in rural China, including some comprehensive treatment processes and relatively novel treatment technologies. Some developed areas in China have considered combined process treatment or introduced some relatively novel treatment technologies through technological innovation. For example, some rural areas in Jiangsu Province have begun to adopt integrated treatment equipment and artificial wetland combined technologies. However, considering China's rural areas' uneven development, China's rural domestic sewage is still mainly treated by decentralized technology on the whole. The widely used decentralized treatment technologies mainly include stable pond technology, constructed wetland treatment systems, land treatment technology, biofilm technology, integrated device treatment technology, septic tank, and so on. In this study, the above five techniques were selected as typical evaluation cases, including four on-site biological methods and one on-site collection method. It is important to explain that considering the practical and focused nature of the evaluation, the study aims to evaluate only the most common methods used or advocated in China today, without considering new treatment technology or combinations of treatment techniques that are less widespread.

EMPIRICAL RESULTS AND DISCUSSION

Construction of comprehensive evaluation index system of rural domestic sewage treatment technology

After correlation analysis, the index combinations with a correlation coefficient higher than 0.8 were selected one by one for judgment and analysis to see whether there was a significant correlation

between the indexes. After screening out the interchangeable indicators, the 17 indicators were adjusted to 14. With the comprehensive evaluation of rural domestic sewage treatment technology as the target level, four primary indicators are the standard level, and 14 secondary indicators are the index level. A brief description of the selected indicator system is as follows.

(1) Economic costs. The economic cost is the measurement of technology on the consumption of various resources and energy materials. Different technologies have different types and quantities of material consumption, which are compared by converting them into unified economic value indexes. The overall investment in technology, operating costs, and subsequent maintenance and replacement costs are included. The total technical investment is a one-time investment in the construction of the project. The total investment in sewage treatment technology is directly proportional to the effective area of sewage treatment facilities. The unit area system construction cost (yuan/m^2) is regarded as a secondary indicator of the economic cost index; the cost mainly includes the cost of treatment agent consumption, land occupation cost, and other energy consumption costs (excluding water resources). The total cost is compared to the amount of sewage treated, and the water treatment cost per ton (yuan/t) is obtained as a secondary indicator; Equipment maintenance costs, equipment depreciation, by-product deductions, and so on, are divided by the aggregate operating costs by the area of the system maintenance and replacement costs (yuan/m^2) as a secondary indicator.

(2) Environmental impact. Domestic sewage treatment technologies can significantly reduce the pressure of rural water pollution. However, they also generate new environmental pollution during operation, including the consumption of clean water resources and the generation of wastewater, greenhouse gases, and sludge from wastewater treatment systems during the operation of their systems. Based on the main pollutants generated in the construction and operation of rural sewage treatment technology, four secondary indicators of water eutrophication affect the potential value, greenhouse effect influences potential value, solid waste and water consumption. By obtaining the price of each environmental impact factor based on the environmental tax concept, the impact weights of each of its secondary indicators are obtained by cross-sectional comparison and analysis as a technical measure of technology's environmental impact.

(3) Technical performance. A point that cannot be ignored in domestic sewage treatment technology is its treatment capacity, including the removal rate of TN/TP, COD/BOD, system operating difficulty, and resource efficiency. With the increasingly stringent requirements of rural water environment, how to improve the maturity of the technology and enhance the efficiency of resource recycling while reducing the difficulty of system operation and adapting to the actual needs of rural residents regarding irrigation or water reuse is a hot spot.

(4) Scope of application. Different domestic sewage treatment technologies have different scopes of application due to differences in process principles. This is mainly reflected in the application area requirements for the amount of water treated and the technology's efficiency. It is also important to consider whether the chosen technology requires additional supporting conditions, such as whether it needs to be excavated and then buried in the ground, whether the treatment temperature needs to be raised, whether it needs a pump to divert the water, and so on. Therefore, the amount of sewage discharged, processing efficiency, and supporting conditions were selected as the three indicators of the scope of application.

Evaluation index weight determination

The expert's opinion is affected by his personal situation. In order to comprehensively solicit the opinions of experts in various fields, we selected 25 experts from sewage treatment technology consultation, supply, design and application (shown in Table 2), mainly working in the related companies.

For the evaluation index system, based on the weight calculation method described above, the weight of each indicator calculated based on the expert consultation results is checked by the consistency test (shown in Table 4).

Table 4 | Rural domestic sewage treatment technology evaluation index weight distribution

First-level	Weight	Sorting	Second-level	Weight
U1: Economic costs	0.0613	4	U11: Water treatment cost per ton	0.0402
			U12: System maintenance and replacement costs	0.0097
			U13: Unit area system construction cost	0.0114
U2: Environmental impact	0.3009	2	U21: Water eutrophication affects the potential value	0.1637
			U22: Greenhouse effect influence potential value	0.0386
			U23: Solid waste	0.0148
			U24: Water consumption	0.0839
U3: Technical performance	0.5204	1	U31: Removal rate of TN and TP	0.2816
			U32: Removal rate of COD and BOD	0.0746
			U33: System operating difficulty	0.0359
			U34: Resource efficiency	0.1283
U4: Scope of application	0.1174	3	U41: Amount of sewage discharged	0.0319
			U42: Processing efficiency	0.0141
			U43: Supporting conditions	0.0714

Quantification of evaluation indicators

The purpose of index quantification is to eliminate differences in the evaluation levels and dimensions of various indexes, thereby facilitating a comprehensive comparison of different technologies to be evaluated. The quantification method adopts the grade assignment method. Through literature research and 20 experts (involving the fields of dioxin control technology research and development, technical evaluation, energy and engineering equipment manufacturing, etc.), a certain index of different control technologies is graded and given an original assignment. Taking the emission concentration of greenhouse gases as an example, it is divided into four levels: poor, normal, good, and excellent. The original assignments correspond to 1, 2, 3, and 4, respectively. The quantitative results of each indicator of the technology to be evaluated are shown in Table 5.

Fuzzy comprehensive evaluation results

Through investigation and literature search, five rural sewage treatment technologies were summarized for comparative evaluation to verify the applicability and practicability of the proposed model, including septic tank technology, stabilization pond technology, land treatment technology, artificial wetland treatment technology and biofilm technology.

In the fuzzy comprehensive evaluation calculation, the last calculation step is to deblur, to obtain the final evaluation score. There are many methods available for deblurring. In this paper, we set the evaluation domain and then the weighted average. Setting the evaluation level domain is to set points for each evaluation level. The scores set in this paper are 4, 3, 2, and 1, corresponding to excellent, good, fair and poor. The evaluation sequence is performed from low-level to high-level. Table 6 and Figure 4 show the evaluation results of the first-level evaluation index. Moreover, the comprehensive evaluation results, which were based on the weights determined by AHP method after defuzzification, are as follows are shown in Table 7 and Figure 5.

Table 5 | Quantitative values of indicators

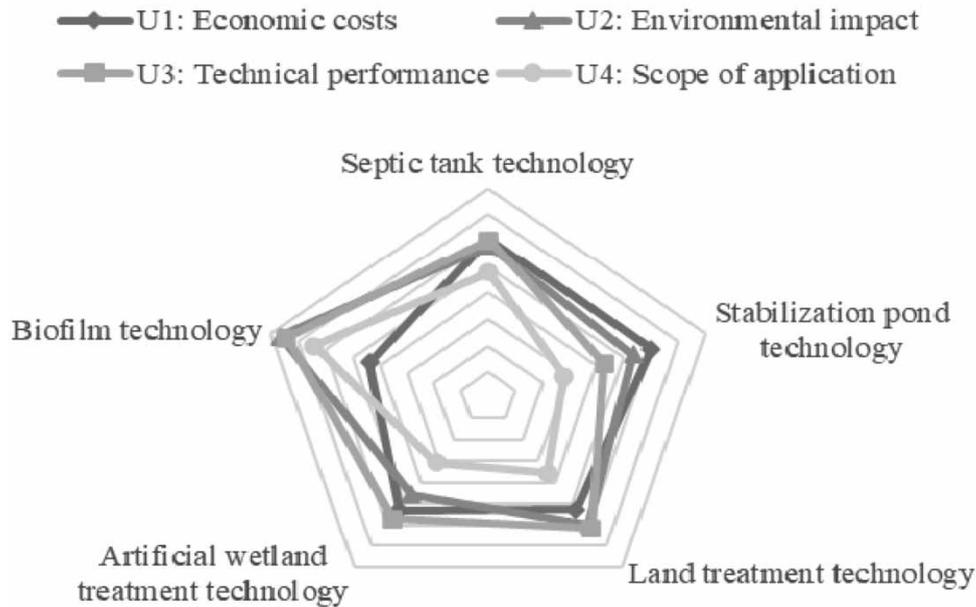|	Treatment technologies				
Index	Biofilm technology	Land treatment technology	Artificial wetland treatment technology	Septic tank technology	Stabilization pond technique
U11	Ordinary (2.0)	Good (3.0)	Good (3.0)	Good (3.0)	Good (3.0)
U12	Ordinary (2.0)	Good (3.0)	Ordinary (2.0)	Good (3.0)	Good (3.0)
U13	Good (3.0)	Poor (1.0)	Ordinary (2.0)	Good (3.0)	Good (3.0)
U21	Excellent (4.0)	Good (3.0)	Ordinary (2.0)	Good (3.0)	Good (3.0)
U22	Good (3.0)	Good (3.0)	Ordinary (2.0)	Good (3.0)	Good (3.0)
U23	Good (3.0)	Good (3.0)	Ordinary (2.0)	Poor (1.0)	Ordinary (2.0)
U24	Excellent (4.0)	Good (3.0)	Good (3.0)	Good (3.0)	Ordinary (2.0)
U31	Excellent (4.0)	Good (3.0)	Good (3.0)	Good (3.0)	Ordinary (2.0)
U32	Ordinary (2.0)	Good (3.0)	Ordinary (2.0)	Good (3.0)	Good (3.0)
U33	Excellent (4.0)	Excellent (4.0)	Good (3.0)	Good (3.0)	Ordinary (2.0)
U34	Excellent (4.0)	Good (3.0)	Good (3.0)	Good (3.0)	Ordinary (2.0)
U41	Ordinary (2.0)	Good (3.0)	Good (3.0)	Good (3.0)	Ordinary (2.0)
U42	Ordinary (2.0)	Good (3.0)	Poor (1.0)	Good (3.0)	Ordinary (2.0)
U43	Excellent (4.0)	Poor (1.0)	Poor (1.0)	Ordinary (2.0)	Poor (1.0)

Table 6 | Fuzzy comprehensive evaluation results of first-level index

No.	Rural domestic sewage treatment technology	U1	Sorting	U2	Sorting	U3	Sorting	U4	Sorting
1	Septic tank technology	3.0000	1	2.9016	3	3.0000	3	2.3920	2
2	Stabilization pond technology	3.0000	1	2.6720	4	2.1433	5	1.3920	5
3	Land treatment technology	2.6265	2	3.0000	2	3.0690	2	1.7841	3
4	Artificial wetland treatment technology	2.6555	2	2.2788	5	2.8567	4	1.5442	4
5	Biofilm technology	2.1867	3	3.8227	1	3.7134	1	3.2159	1

Analysis and discussion of results

(1) The research scope determination method in this paper is an improvement over previous studies. Based on the rural domestic sewage treatment market conditions and life cycle theory, the full life cycle inventory analysis and impact evaluation are integrated into the construction of a comprehensive evaluation model for rural domestic sewage treatment technologies to ensure the indicator's science and integrity system. This paper uses hierarchical analysis to determine the indicators' weights, and measures the relative importance between the indicators by comparing two to two, which is a relatively common method in previous studies. However, this paper adopts a nine-scale method for determining the judgment matrix, which significantly reduces the error of experts' judgment on the importance of indicators, comparing Hao *et al.*'s weight allocation method (Hao *et al.* 2012). In the evaluation index system of rural domestic sewage treatment technology constructed by AHP and the Delphi expert consultation method, the technical performance and environmental impact indicators of rural domestic sewage treatment technology have the highest weight, which is the core of the technical evaluation. It can be seen that in the face of the pressure of continued deterioration of the rural ecological environment, the technical performance of the sewage treatment effect is much higher than other indicators. Besides, the impact on the environment has also received much attention, with the

Figure 4 | Evaluation results of first-level index.

Table 7 | The results of comprehensive evaluation

Evaluation index	Technical types				
	Biofilm technology	Land treatment technology	Artificial wetland treatment technology	Septic tank technology	Stabilization pond technique
U11	0.1122	0.1683	0.1683	0.1683	0.2244
U12	0.027	0.0405	0.027	0.0405	0.0405
U13	0.048	0.016	0.032	0.048	0.048
U21	0.9168	0.6876	0.4584	0.6876	0.6876
U22	0.162	0.162	0.108	0.162	0.162
U23	0.0621	0.0621	0.0414	0.0207	0.0414
U24	0.4696	0.3522	0.3522	0.3522	0.2348
U31	0.798	0.5985	0.5985	0.5985	0.399
U32	0.1056	0.1584	0.1056	0.1584	0.1584
U33	0.1016	0.1016	0.0762	0.0762	0.0508
U34	0.3636	0.2727	0.2727	0.2727	0.1818
U41	0.0678	0.1017	0.1017	0.1017	0.1017
U42	0.0298	0.0447	0.0149	0.0447	0.0298
U43	0.3028	0.0757	0.0757	0.1514	0.0757
Total score	3.5669	2.8422	2.4327	2.8829	2.4359
Sorting	1	2	5	3	4

second-largest weight. In the evaluation system derived by Zhao, the environmental impact assessment only accounts for 0.180, which is the last one (Zhao 2019). The main reason for this research to improve on this point is that rural China has developed to such an extent that economic development is no longer the first objective, and the ecological environment is equally important. Among the technical performance indicators, the indicators that reflect the effect of pollutant removal account for half, which is the critical indicator that experts pay attention to and the
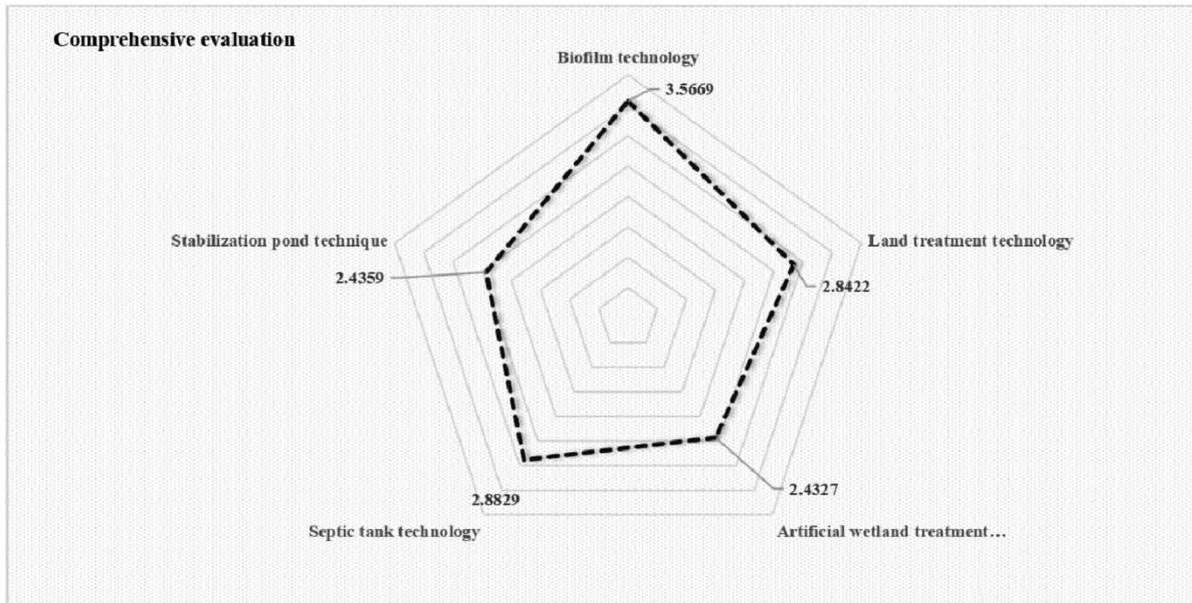
Figure 5 | Comprehensive evaluation results.

most critical advantage of the technology. Among the environmental impact indicators, the indicators related to the greenhouse effect are explicitly introduced. This shows that the impact of greenhouse gas emissions on the environment has increasingly attracted people's attention. For example, in the evaluation system established by Shen *et al.*, indicators related to the greenhouse effect are ignored. Emphasis was also placed on the importance of the environmental impact of resource consumption and the integration of ecological damage and resource consumption into the evaluation system. In the economic cost index, the conventional water treatment cost index is emphasized and the depreciation expense index is set, which makes the entire cost accounting system more perfect. Among the relevant scope indicators, the 'Supporting conditions required by technology' is an indicator aimed at the differences in rural China, with a weight ratio of 60.8%. The construction of the rural domestic sewage treatment technology index system accurately reflects the current social concern for the rural ecological environment.

(2) According to the results of the fuzzy comprehensive evaluation, biofilm technology and septic tank technology ranked as the top two in the overall evaluation. The scores of biofilm technology and septic tank technology are 3.5669 and 2.8829, respectively. Biofilm technology is a typical application of materials science in the field of sewage treatment, combining membrane technology and biotechnology. Biofilm technology uses membrane technology to filter out large-diameter molecules, organic matter, and particulate matter. On the other hand, it uses biotechnology to decompose organic matter and ammonia nitrogen in sewage. As biofilm technology has a wide range of practicability and application, it ranks first in terms of high performance and environmental impact indicators, so it also ranks first in a comprehensive evaluation. Septic tank technology is the primary type of technology that promotes the toilet revolution in cold and dry areas. The technology itself has little impact on the environment and has a high score in terms of economic cost, having distinct investment advantages but is unable to cope with compound pollution. Land treatment technology has apparent advantages in environmental impact indicators, but it is inferior in terms of technical performance and scope of application, ranking third overall. The disadvantages of the stabilization pond technology and the constructed wetland technology are similar, both having low scores in technical performance and ranking in the bottom. In practical applications, these rural domestic sewage treatment technologies work

well for rural sewage, implying that evaluation results in this paper are in line with reality. What is more, the evaluation methods are scientific and practical.

(3) According to the ranking results of the first-level indicators, we can see that among the four first-level indicators, the performance of different types of rural domestic sewage treatment technologies varies greatly. The optimization of biofilm technology, septic tank technology and land treatment technology has significant advantages in terms of technical performance indicators, leading to the advantages of its comprehensive evaluation results. Because these three technologies can effectively remove pollutants from rural domestic sewage, they meet the needs of the rural ecological environment in China at present. They can reduce the discharge of pollutants and curb the destruction of the rural ecological environment. Therefore, such technologies show apparent advantages in terms of environmental impact indicators. While for artificial wetland technology and stabilization pond technology, the climate and environmental impact fluctuations are relatively large; for example, winter after sewage treatment significantly reduces the effect (Ma & Yang 2019), so in this indicator, scores are not high.

CONCLUSIONS AND RECOMMENDATIONS

This paper uses AHP and fuzzy comprehensive evaluation methods to construct a comprehensive evaluation index system for rural domestic sewage treatment technology. Five potential rural sewage treatment technologies were selected as empirical research objects to verify the proposed model. Comprehensive evaluation and analysis were conducted. The main conclusions of this study and recommendations are as follows.

Main conclusions

(1) The empirical research results show that the three technologies of biofilm technology, septic tank technology and land treatment technology rank in the top three in rural domestic sewage treatment technologies. Therefore, optimizing the performance of the technology is the core of promoting and applying water treatment technology in the field of rural ecological environment. This is because they have an excellent environmental protection effect mainly, and are conducive to reducing emissions such as greenhouse gas emissions and other pollutants. Biofilm technology, septic tank technology and land treatment technology have made a positive contribution to environmental protection and should be promoted and applied with emphasis. The evaluation results of the model reflect the objective reality of the rural ecological environment and the differences in the selection of advanced and applicable technologies for sewage treatment technology in rural China.

(2) At present, the stabilization pond technology and constructed wetland technology are mainly used in the southern regions, with a relatively developed economy and abundant water resources. With the promotion of China's rural revitalization policy, most of the rural areas in southern China have started to urbanize or have been annexed by urban expansion, and their economic conditions can afford the cost of pipe network deployment. As the living situation in the southern region is gradually converted to small settlements, the southern region is gradually phasing out stabilization pond technology and constructed wetland technology, and gradually transforming into small centralized sewage treatment plants or other high-performance sewage treatment technologies. Although stabilization pond technology and constructed wetland technology can effectively control costs and have obvious investment advantages, their poor performance and low processing efficiency make their overall rankings low.

(3) This paper uses a monetization method to quantify the environmental impact of rural sewage treatment technology. This effectively solves the disadvantage that the traditional target distance method cannot unify ecological destruction and resource consumption into an evaluation system and ignores the impact of resource consumption on the environment. What's more, the technical evaluation results offer increased accuracy and credibility.

Recommendations

(1) In order to effectively control the deterioration of the rural aquatic environment, rural domestic sewage treatment technology should focus on improving its technical performance and positive environmental impact. The state government should also increase the corresponding technical research, development efforts and financial support to make a further promotion of rural domestic sewage treatment technology.

(2) The previous ecological treatment technology (constructed wetland technology, stabilization pond technology, land treatment technology) has been unable to cope with the complexity of rural domestic sewage components. At present, it is difficult for the performance and efficiency of ecological treatment technology to meet the national emission standards and the environmental protection requirements for water bodies. The next step is to increase the proportion of biofilm technology and septic tank technology in order to achieve the purpose of strengthening the purification capacity of the system.

(3) The future research direction of the evaluation system should focus on the following:

  (1) The collection of data on the environmental impact of rural domestic sewage treatment technology, expanding the range of typical pollutants and increasing the reliability of results.

  (2) Improvement of the life cycle assessment model of rural domestic sewage treatment technology, includes research on environmental damage mechanisms, economic cost control models, the establishment of an appropriate environmental impact-health damage model, environmental impact economic evaluation model, and so on.

  (3) The research ideas and evaluation methods can be extended to other sewage treatment technologies. The universal characteristics of sewage treatment technology can be found through the model, which can also be tried and used in the evaluation of other technologies. This is operable and cutting-edge.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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