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Rural domestic sewage treatment in Northeast cold region of China: rational evaluation of technology options

Huating Jiang[a], Junqian Tang[a], Xiaohan Li[a], Wanyi Fang[a], Ya Bian[b], Xin Mi[a], Dexin Shan[c,*], Yingjie Dai[a,*]

[a]*College of Resources and Environment, Northeast Agricultural University, No. 600 Changjiang Road, Xiangfang District, Harbin 150030, China, emails: dai5188gmail.com (Y. Dai), 1192350923@qq.com (H. Jiang), 1196002729@qq.com (J. Tang), 1825998729@qq.com (X. Li), 1043680663@qq.com (W. Fang), 2028148927@qq.com (X. Mi)*
[b]*College of Life Sciences, Northeast Agricultural University, No. 600 Changjiang Road, Xiangfang District, Harbin 150030, China, email: 1728459191@qq.com*
[c]*College of Landscape Architecture and Life Science, Chongqing University of Arts and Sciences, No. 319 Honghe Road, Yongchuan District, Chongqing 402168, China, email: 410932396@qq.com*

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ABSTRACT

This research aims to propose reasonable solutions for reference based on the characteristics of rural domestic sewage of the cold regions in Northeast of China (CRNC). Analytical hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE) are used to analyze and calculate the weight of rural domestic sewage treatment indicators in the cold northeast area. The AHP method is used to optimize and calculate the CRNC's rural domestic sewage treatment indicators, and obtain the comprehensive weights of 15 indicators in the three standard layers and the indicator layer. It further analyzes the weight of the secondary indicators to determine the standard of the evaluation indicators. The FCE method is used to calculate the fuzzy measure and membership degree. Finally, AHP weighted summation is used to determine the applicability of the technical choice. The calculation results determine the best technology combination scheme of the three processing methods: (1) sequential batch reactor = 0.820, constructed rapid infiltration = 0.701; (2) soil infiltration technology = 0.803, stable pond technology = 0.585; (3) constructed wetland treatment technology = 0.787, septic tank technology = 0.585. Schemes 1, 2, and 3 are used for centralized treatment mode, decentralized treatment mode, and treatment mode for water environment sensitive areas, respectively. The research results provide good theoretical support for the technical selection of different treatment modes in cold regions.

Keywords: Analytical hierarchy process; Removal rate; Rural area; Sewage treatment

1. Introduction

China's rural area has a large population which has caused a large amount of wastewater in such area. Due to the slow and backward economic development in part of the rural area, the domestic sewage treatment is poor. China's rural sewage treatment rate is only about 22% in 2019 [1]. Economic development and environmental characteristics such as temperature, topography, air humidity have become a serious obstacle to rural sewage treatment in China, especially the cold regions in the Northeast of China (CRNC). This is a vast land but with a low population and extremely low temperature which is even as low as –20°C –30°C in winter. Hence, the rural domestic sewage treatment methods are imperfect due to the restriction of a low-temperature environment. With such concern, we need

* Corresponding authors.

to evaluate new rural domestic sewage treatment models, meanwhile, apply the appropriate technology in CRNC.

Due to the characteristics of the rural area, the treatment of domestic sewage has been divided into centralized treatment, decentralized treatment, and water-sensitive area treatment modes. The centralized governance model is mainly to apply the system of the sequential batch reactor (SBR) and hybrid wastewater treatment to areas where with a population of no more than 5,000, for example, Halcioglu town of Istanbul in Turkey [2]. The previous study shows discovered the combined use of septic tanks and sand filters and equipped with intermittent wastewater treatment methods to treat sewage in rural areas in Campinas of Brazil, and finally, wastewater became reusable in agricultural activities [3]. A gravity flow canon-like pilot plant membrane bioreactor (MBR) treats surface water from northern China in winter has been designed [4]. This study has shown that the composite process exhibits good biological stability and sustainability in different seasons, which demonstrates the feasibility of the composite process [4]. For the decentralized governance model, there are some reports on different technology combinations. Some studies found that the chemical oxygen demand (COD), NH_4^+–N, suspended solids (SS), and total phosphorous (TP) in the sewage has reached the discharge standards for rural sewage treatment in China by applying the system of hydrolytic acidification, biological contact oxidation, and MBR. The removal rates of COD and NH_4^+–N were 85.0% and 80.0%, respectively, and the equipment had a good operating effect [5]. Son et al. [6] researched that in removing the organic pollutants and nutrients contained in the scattered rural domestic sewage in Gongju of South Korea, three parts were used to form a combination: anaerobic fecal tank and absorbent biological filter and constructed wetlands that flow up and down [6]. The combination has the benefits of high performance, low cost, and effective treatment of decentralized rural sewage [6]. Some countries and regions have water environment sensitive area, therefore, different technology combinations are required to serve this specific area. The combined process of anaerobic and water droplet aeration and constructed wetland was used to treat domestic sewage in rural China. It has an average removal rate of 74.5% (COD), 57.2% (total nitrogen (TN)), 59.5% (TP), 59.0% (NH_4^+–N), and 91.6% (SS) [6]. In the analysis of pollutant removal by the combined process, the constructed wetland has the highest removal rate of COD, TN, TP, and NH_4^+–N [7]. The combination of different technologies is very effective in removing pollutants from water in various regions of China. The combination of rapid infiltration technology and constructed wetland technology to treat rural domestic sewage in Guilin city of China, and found that the rapid infiltration technology and the integrated biological wetland system worked well in all seasons, effectively increasing the removal rate of COD. The removal rate of TN and TP also achieved 87.0% and 85.9%, respectively [8]. It was found that although the removal rate of COD, TN, and TP still reached 81.8%, 76.1%, and 70.4%, respectively, although it was relatively low in winter [8]. The technical choices under these governance models have had an effective impact and pertinence on the local economy, population, and environmental treatment, especially on rural domestic sewage. At the same time, these models have a good effect on the treatment of pollutants in rural domestic sewage. However, these governance models have certain limitations. There are no effective explanations for different climatic conditions in different latitudes, and it is hard to determine whether they are applicable to rural domestic sewage treatment in areas where are different from their environment or even in extreme climates.

Rural residents live relatively scattered and are restricted by the geographical environment, the treatment of rural domestic sewage requires a combination of multiple treatment technologies. When the rural domestic sewage treatment model is used, it is necessary to evaluate and screen various indicators of the treatment process through the model. There are three sustainability pillars that need to be considered in the study of the sustainable development of wastewater systems, which are the environment, society, and economy. The wastewater treatment facilities (WWTF) will be evaluated through the life cycle method. Eighteen indicators from the environmental life cycle, economic performance, and social life cycle are firstly evaluated, and followed by using fuzzy logic analysis for evaluation and identification, eventually, the sustainable WWTF will be determined through the Sustainable Development Global Index. Alternative method development for selecting the best WWTF will be based on environmental factors, meanwhile, use social life cycle assessment and fuzzy analysis to determine a suitable WWTF to achieve sustainable water management globally [9]. The best process will be determined by evaluating wetland, technical, environmental, and social impacts based on the economy. By establishing an evaluation method of wetland treatment technology, an evaluation indicator system has been built up by analytical hierarchy process (AHP) which will use the entropy weight method to calculate indicator weights and organizational method to rank the selected indicators. Through the final screening of the best technology, a set of evaluation methods for wetland treatment technology will be established [10].

Through the combination of fuzzy set theory (FST) and the AHP method, a preliminary assessment of the treatment of olive factory wastewater (OFW) has been carried out [11]. Some studies show that use multiple standards to integrate factors related to environmental and economic issues is useful and feasible. An analysis hierarchy model by OFW method and different fuzzy membership functions of FST are used for calculation [12]. In this process, the AHP method is used to determine the relative importance of each criterion. The research shows that the AHP method is highly applicable in using the weighted linear combinations to compare different important environmental-related scenarios and economic goals [12–14].

Based on the characteristics of rural domestic sewage in CRNC, the research proposes a reasonable technical selection plan to provide a certain feasibility reference for the distribution of different rural areas in the cold area. This research uses AHP and fuzzy comprehensive evaluation (FCE) method to give priority to the calculation of the treatment indicators of rural domestic sewage in CRNC. The calculation should be done by following the weights of the three criteria levels of rural domestic sewage, and 15 evaluation indicators in the indicator level, and finally calculate the comprehensive weights. Then analyze the weight distribution of the secondary indicators, and further determine the evaluation indicators standards as well as classify by establishing a set of evaluation factors. First, analyze the degree of ambiguity and applicability in each governance mode by establishing evaluation factors and weight calculations. According to the results of each weight, the advantages and disadvantages of the three governance models are evaluated, namely, the centralized governance model, the decentralized governance model, and the water environment sensitive area, respectively. Through the calculation of priority indicator weights, the research judges, and selects the corresponding technical feasibility under the reasonable plan through the calculation results, and the results are used to select various governance methods. This work provides a reference for analyzing the evaluation results of treatment models for rural sewage in CRNC.

2. Methods

2.1. Establishing an evaluation indicator system

To establish the evaluation indicator, this paper researched and constructed a tightly progressive hierarchical structure of "specific objectives-selection and principles-specific indicators." From the three levels of economic benefit, technical performance, and environmental impact. According to literature research, on-site investigation, and data sorting, various indicators are further screened and analyzed. Due to the different properties in different regions, the factors that affect the rural domestic sewage treatment model are also different [15], the preliminary results are shown in Table 1.

2.2. AHP method to optimize the evaluation indicators system

By optimizing the evaluation indicators system, 50 evaluation indicators were screened and optimized in the table, and got the final 15 evaluation indicators. The indicators system conforms to the principles of scientificity, practicality, comparability, conciseness, systematicness, and operability [16]. Data that has met the availability and applicability and the optimization results are shown in Table 2. Finally, the indicator weights were determined and the evaluation criteria, and build models based on the AHP method. The hierarchical single ranking method, sets B as a judgment matrix of a certain level, λ_{max} as the maximum eigenvalue, delete W as the corresponding

Table 1
Preliminary results of comprehensive evaluation indicators for rural domestic sewage treatment models

Target layer	Criterion layer	Indicator layer	
Rural domestic sewage treatment model	Economic benefit	(1) Local funds	(8) Unit construction area
		(2) Operating costs	(9) Unit energy consumption
		(3) Unit investment	(10) Service population ratio
		(4) Land cost	(11) Equipment maintenance
		(5) Construction area	(12) Economic benefit
		(6) Consumption	(13) Process complexity
		(7) Reasonable scale	(14) Equipment newness
	Technical performance	(15) Total sewage treatment	(25) Total nitrogen removal rate
		(16) COD removal rate	(26) Total phosphorus removal rate
		(17) BOD_5 removal rate	(27) Total dissolved solids removal rate
		(18) SS removal rate	(28) Stability of effluent compliance rate
		(19) NH_4^+–N removal rate	(29) Pathogenic microorganism removal rate
		(20) pH compliance rate	(30) Stability of pollutant removal rate
		(21) Water color	(31) Process operation stability
		(22) Water resistance	(32) Difficulty of management and operation
		(23) Technology maturity	(33) Sludge treatment
		(24) Process simplicity	
	Environmental impact	(34) Noise impact level	(43) Malodorous gas influence
		(35) Greening degree	(44) Regional temperature influence
		(36) SO_2 production	(45) Pathogenic microbial biomass
		(37) NO_x production	(46) Waste residue generation
		(38) CO_2 production	(47) Amount of sand
		(39) CH_4 production	(48) Impact on nearby residents
		(40) H_2S production	(49) Resource utilization
		(41) NH_3 production	(50) Ecological balance
		(42) Sludge production	

Annotation: biochemical oxygen demand (BOD_5), hydrogen ion concentration (pH), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3).

Table 2
Optimization result of a comprehensive evaluation indicator system for a rural domestic sewage treatment model

Target layer	Criterion layer	Indicator layer
Rural domestic sewage treatment models in cold regions of Northeast China	Economic benefit (B_1)	Local funds and unit investment (C_1)
		Operating costs (C_2)
		Construction area and service population ratio (C_3)
		Sewage water volume (C_4)
	Technical performance (B_2)	COD removal rate (C_5)
		BOD_5 removal rate (C_6)
		NH_4^+–N removal rate (C_7)
		SS removal rate (C_8)
		Process applicability (C_9)
		Stability of effluent reaching standard (C_{10})
		Ease of management and operation (C_{11})
	Environmental impact (B_3)	Malodorous gas influence (C_{12})
		Noise level (C_{13})
		Regional environmental temperature influence (C_{14})
		Impact on local residents (C_{15})

eigenvector, and normalize the weight of each indicators of the *B* matrix which obtained by normalizing *W*. AHP method will be calculated using Eqs. (1)–(3):

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(BW)_i}{W_i} \quad (1)$$

$$C_I = \frac{\lambda_{\max} - n}{n-1} \quad (2)$$

$$C_R = \frac{C_I}{R_I} \quad (3)$$

The average random consistency indicator R_I is shown in Table 3. Based on the data being collected, AHP is applied to establish the model, and the following results are calculated. Python, yaahp, and WPS excel software were used to use the analytic hierarchy process for model construction and single sorting, and calculation of judgment matrix and criterion weight to get the total sorting. The corresponding evaluation indicator system which is established by applying the AHP method is shown in Fig. 1.

2.3. Economic benefit indicator calculation

According to the field survey data of the rural domestic sewage treatment model, the cost of unilateral water treatment investment is US$1,000–2,500/m^3, and the conversion function of local funds and unit investment has been constructed, meanwhile, the results are calculated using Eq. (4):

$$R_1 = \frac{2{,}500 - X}{2{,}500 - 1000} = \frac{2{,}500 - X}{1{,}500} \quad (4)$$

According to the field survey data of the rural domestic sewage treatment model, the operation cost of treating unilateral water is US$0.01–0.04/m^3, and the operation cost budget conversion function is constructed with results calculated using Eq. (5):

Table 3
Average random consensus indicator R_I

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

$$R_2 = \frac{0.04 - X}{0.04 - 0.01} = \frac{0.04 - X}{0.03} \quad (5)$$

According to the field survey data of the rural domestic sewage treatment model, the ratio of the construction area of sewage treatment facilities to the service population is 0.1–0.4 m^2/person and the conversion function of the ratio is constructed with results calculated using Eq. (6):

$$R_3 = \frac{0.4 - X}{0.4 - 0.1} = \frac{0.4 - X}{0.3} \quad (6)$$

According to the field survey data of the rural domestic sewage treatment model, the amount of sewage treated per unit is 45–140 m^3/person/y, and the budget conversion function of the sewage water volume is established and the results are calculated using Eq. (7):

$$R_4 = \frac{140 - X}{140 - 45} = \frac{140 - X}{95} \quad (7)$$

2.4. Establishment of evaluation model

Through the determined evaluation indicator system, the evaluation factors are obtained, and the indicators are divided into two categories: quantitative and qualitative. The total set *U* and its subsets u_1, u_2, u_3…were set up.

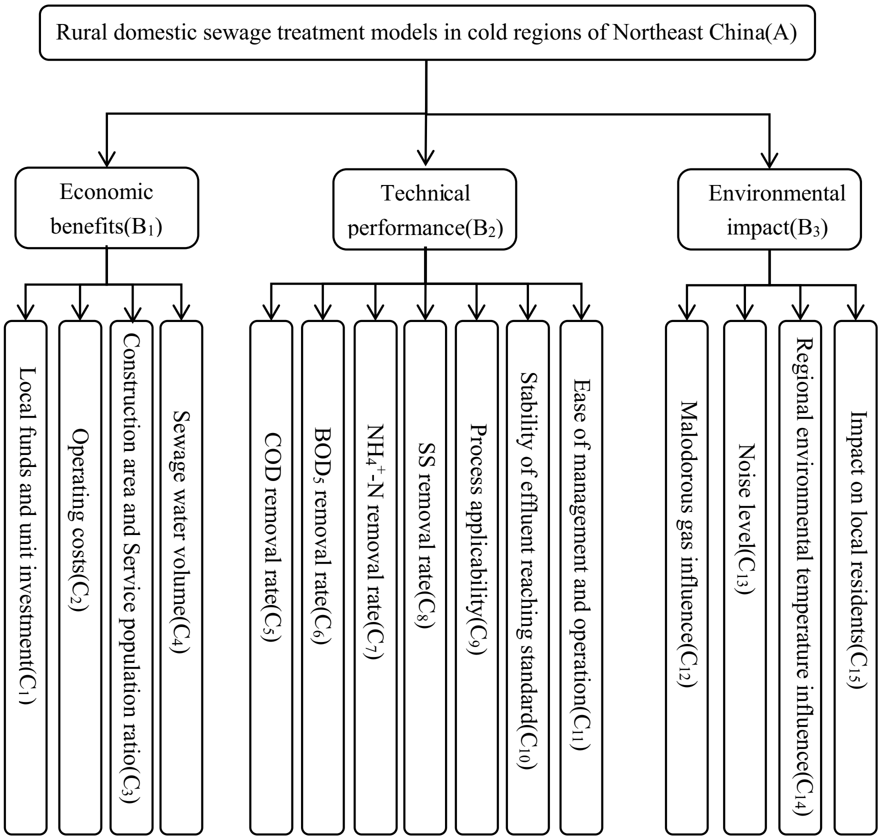

Fig. 1. Evaluation indicator system of rural domestic sewage treatment efficiency in the cold regions of Northeast China.

The weight set W of the evaluation indicator system by the AHP method was determined.

2.5. Calculation of evaluation value by FCE method

This research assumes that the annotation set V = {worst, worse, better, best} to describe the n levels of the state of each factor. In order to obtain accurate evaluation results, each indicator was evaluated. Each indicator value in the evaluation indicator system is obtained through the FCE method. From the scoring standards of each indicator, the standardized evaluation value R_L of each evaluation mode indicator is obtained. Then the weight set W is multiplied by the indicator evaluation result R_L and add. Finally, the final score M of each evaluation mode is determined by calculation. The best governance model is finally determined as follows, and finally, the maximum value of M is the final selection model result Eq. (8):

$$M = R_{\mathrm{kL}} \times W = \begin{pmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ R_{k1} & R_{k2} & \cdots & R_{\mathrm{kn}} \end{pmatrix} \times \begin{pmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{pmatrix} = \begin{pmatrix} M_1 \\ M_2 \\ \vdots \\ M_k \end{pmatrix} \tag{8}$$

where W is the weight value of each indicator; R_{kL} is the score value of the Lth evaluation indicator of the k-th governance model; M_k is the evaluation score of the k-th governance model. M_k is the evaluation score of the k-th governance efficiency, and finally, the maximum value of M is the final selection efficiency result.

2.6. Comprehensive evaluation value calculation

The degree of membership is used to indicate the performance of a certain indicator for a certain system. The larger the indicator value of the positive indicator, the better, the smaller the indicator value of the negative indicator, the better.

The degree of membership was calculated $h(I)$: when $0 < I \leq 1$, $h(I) = 1$; when $I > 1$, $h(I) = e–(I–1)$. $I_i = S_i/C_i$ (positive indicators); $I_i = C_i/S_i$ (negative indicators). C_i represents the actual value. Degree of membership $0 \leq h(I) \leq 1$, the greater the value, the greater the degree of membership; the smaller the value, the smaller the degree of membership.

In the calculation, the membership degrees of different criterion layers and indicator layers are sorted from large to small, and the corresponding fuzzy measures (weight values) are calculated. The fuzzy integral evaluation model is used to calculate the evaluation value. The calculation formula is Eq. (9):

$$\int x h\left(x_i\right) \times g\left(\cdot\right) = \sum_{i=1}^{n} \left[h\left(x_i\right) \cdot H\left(x_i\right) \right] \tag{9}$$

2.7. Use AHP to calculate weighted summation ranking to choose a solution

The indicator weights of the AHP method were used to judge the advantages, disadvantages, and feasibility weights of different modes and technologies, and add them to the calculation. (√ means that the technology has the advantage of this indicator, — means there is no advantage of this indicator), (*G* is the corresponding code of each technology), and (*C* is the corresponding code of the above indicators).

3. Results

3.1. Results of the evaluation of criterion layer

The literature and field inspections were reviewed to give weight to the criterion layer. Python, yaahp, and WPS excel software were used to use the analytic hierarchy process for model construction and single sorting, and the calculation of judgment matrix and criterion weight to get the total sorting. According to the AHP method, the calculation was constructed the judgment matrix of the criterion layer, namely, the relatively important weights of the indicator factors of the nine-scale matrix *A–B* W_i needs to be calculated and judged when $C_R = 0.0079 < 0.1$ and $\lambda_{\max} = 3.0092$.

$$\text{Matrix } A\text{–}B \quad \begin{array}{c} \\ B_1 \\ B_2 \\ B_3 \end{array} \begin{array}{c} \begin{array}{ccc} B_1 & B_2 & B_3 \end{array} \\ \begin{bmatrix} 1 & 3 & 2 \\ 1/3 & 1 & 1/2 \\ 1/2 & 2 & 1 \end{bmatrix} \end{array}$$

$$\text{Relative importance weight } W_i = \begin{bmatrix} 0.5396 \\ 0.1634 \\ 0.2970 \end{bmatrix}$$

In the judgment to calculate the indicator weights of the comprehensive evaluation criteria for the rural domestic sewage treatment model, it can be seen from Table 4, that the weights W_i in the economic benefits, technical performance, and environmental impact are 0.5396, 0.1634, 0.2970, respectively, and AW_i is the average value of W_i, hence $\lambda_{\max} = 3.0092$ can be calculated by formula $AW_i/W_i = \lambda_{\max}$.

Regarding $C_I = \frac{\lambda_{\max} - n}{n-1} = 0.0046$, Table 3 shows that $n = 3$, $R_I = 0.58$, so the random consistency ratio of matrix *A–B* is given by $C_R = \frac{C_I}{R_I}$ which is calculated as 0.0079 (<0.1), indicating that the matrix meets the consistency. Based on the above, the economic benefits, technical performance, and environmental impact indicators can be calculated under each criteria level.

Table 4
Summary of the results of the nine-scale matrix judgment at the criterion layer (matrix *A–B*)

A–B	B_1	B_2	B_3	W_i
B_1	1	3	2	0.5396
B_2	1/3	1	1/2	0.1634
B_3	1/2	2	1	0.2970

3.2. Evaluation result of economic benefit indicator (B_1)

According to the calculation of the above AHP method, the economic benefit evaluation indicator matrix B_1–C could be constructed. The study calculated and judged the relatively important weight W_i of each indicator factor of the nine-scale matrix B_1–C and the consistency test. When $C_R = 0.0415 < 0.1$, $\lambda_{\max} = 4.1120$, the indicators of the nine-scale matrix B_1–C can be calculated and judged. W_i is the relatively important factor, the results are shown in Table 5.

$C_I = \frac{\lambda_{\max} - n}{n-1} = 0.0373$, Table 3 shows that $n = 4$, $R_I = 0.90$, so the random consistency ratio of matrix B_1–C can be calculated as 0.0415 (<0.1), indicating that the matrix meets the consistency. Finally, the indicator calculation under the economic benefit layer could be calculated.

3.3. Evaluation result of technical performance indicator (B_2)

According to the calculation of the above AHP method, the technical performance evaluation indicator matrix B_2–C could be constructed. The study calculated and judged the relatively important weights W_i of each indicator factor of the nine-scale matrix B_2–C and the consistency test. When $C_R = 0.0407 < 0.1$, $\lambda_{\max} = 7.3221$, the indicators of the nine-scale matrix B_2–C can be calculated and judged. W_i is the relatively important factor, the results are shown in Table 6.

Where $C_I = \frac{\lambda_{\max} - n}{n-1} = 0.0537$, Table 3 shows that $n = 7$, $R_I = 1.32$, so the random consistency ratio of matrix B_2–C can be calculated as 0.0407 (<0.1), indicating that the matrix meets the consistency. At last, the indicator calculation under the technical performance layer could be calculated.

3.4. Evaluation results of environmental impact indicator (B_3)

According to the calculation of the above AHP method, the environmental impact evaluation indicator matrix B_3–C could be constructed. The study calculated and judged the relative important weight W_i of each indicator factor of the nine-scale matrix B_3–C and check the consistency. When $C_R = 0.0263 < 0.1$, $\lambda_{\max} = 4.0709$, the indicators of the nine-scale matrix B_3–C can be calculated and judged. W_i is the relatively important factor, the results are shown in Table 7.

Where $C_I = \frac{\lambda_{\max} - n}{n-1} = 0.0236$, Table 3 shows that $n = 4$, $R_I = 0.90$, so the random consistency ratio of matrix B_3–C can be calculated as 0.0263 ($C_R < 0.1$), indicating that the matrix meets the consistency. The indicator calculation under the environmental impact layer could be calculated.

3.5. Determination of the comprehensive weight of each indicator

In order to sort the comprehensive evaluation of the rural domestic sewage treatment model in CRNC, the comprehensive weight of each evaluation indicator was need to determine and carry out the overall ranking. The results are shown in Table 8. The secondary weight indicator and the weight distribution of the indicator layer, are shown in Fig. 2.

3.6. Determination of the evaluation indicator standard

The applicability evaluation indicator for the rural domestic sewage treatment model in CRNC includes two indicators, a quantitative indicator, and a qualitative indicator. This paper presented 15 evaluation indicators in total and standardized each indicator for comparison. The economic benefit indicators are as Eqs. (4)–(7), respectively. The other evaluation indicators are shown in Table 9.

Table 5
Summary of the results of the nine-scale matrix of the economic benefit layer (matrix B_1–C)

B_1–C	C_1	C_2	C_3	C_4	W_i
C_1	1	1/2	3	2	0.2733
C_2	2	1	3	5	0.4860
C_3	1/3	1/3	1	2	0.1426
C_4	1/2	1/5	1/2	1	0.0982

Table 6
Summary table of the results of the nine-scale matrix of the technical performance layer (matrix B_2-C)

B_2–C	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	W_i
C_5	1	1	2	2	3	1/2	1/2	0.1412
C_6	1	1	2	2	3	1/3	1/3	0.1276
C_7	1/2	1/2	1	2	4	1/4	1/4	0.0949
C_8	1/2	1/2	1/2	1	3	1/3	1/3	0.0827
C_9	1/3	1/3	1/4	1/3	1	1/5	1/4	0.0471
C_{10}	2	3	4	3	5	1	1	0.2568
C_{11}	2	3	4	3	4	1	1	0.2498

3.7. Establishment of evaluation model of rural domestic sewage treatment mode in CRNC

Based on the evaluation indicator system of rural domestic sewage treatment mode in the cold northeast region determined above, a set of evaluation factors is obtained. The 15 indicators are divided into qualitative and quantitative indicators, as shown in Table 10:

U = {Economic benefits (u_1), Technical performance (u_2), Environmental impact (u_3)},

u_1 = {Local funds and unit investment (u_{11}), Operating costs (u_{12}), Construction area and Service population ratio (u_{13}), Sewage water volume (u_{14})},

u_2 = {COD removal rate (u_{21}), BOD_5 removal rate (u_{22}), NH_4^+–N removal rate (u_{23}), SS removal rate (u_{24}), Process applicability (u_{25}), Stability of effluent reaching standard (u_{26}), Ease of management and operation (u_{27})},

u_3 = {Malodorous gas influence (u_{31}), Noise level (u_{32}), Regional environmental temperature influence (u_{33}), Impact on local residents (u_{34})}.

Table 7
Summary of the results of the nine-scale matrix of the environmental impact layer (matrix B_3–C)

B_3–C	C_{12}	C_{13}	C_{14}	C_{15}	W_i
C_{12}	1	1/2	1/3	2	0.1671
C_{13}	2	1	1/2	2	0.2616
C_{14}	3	2	1	3	0.4531
C_{15}	1/2	1/2	1/3	1	0.1182

Table 8
Comprehensive weight table of the indicator system

Target layer	Criterion layer	Weights	Indicator layer	Weights	Comprehensive weight
Rural domestic sewage treatment models in cold regions of Northeast China	Economic benefits (B_1)	0.540	Local funds and unit investment	0.273	0.091
			Operating costs	0.486	0.162
			Construction area and Service population ratio	0.143	0.048
			Sewage water volume	0.098	0.033
	Technical performance (B_2)	0.163	COD removal rate	0.141	0.047
			BOD_5 removal rate	0.128	0.043
			NH_4^+–N removal rate	0.095	0.032
			SS removal rate	0.083	0.028
			Process applicability	0.047	0.016
			Stability of effluent reaching the standard	0.257	0.086
			Ease of management and operation	0.250	0.083
	Environmental impact (B_3)	0.297	Malodorous gas influence	0.167	0.056
			Noise level	0.262	0.087
			Regional environmental temperature influence	0.453	0.151
			Impact on local residents	0.118	0.039

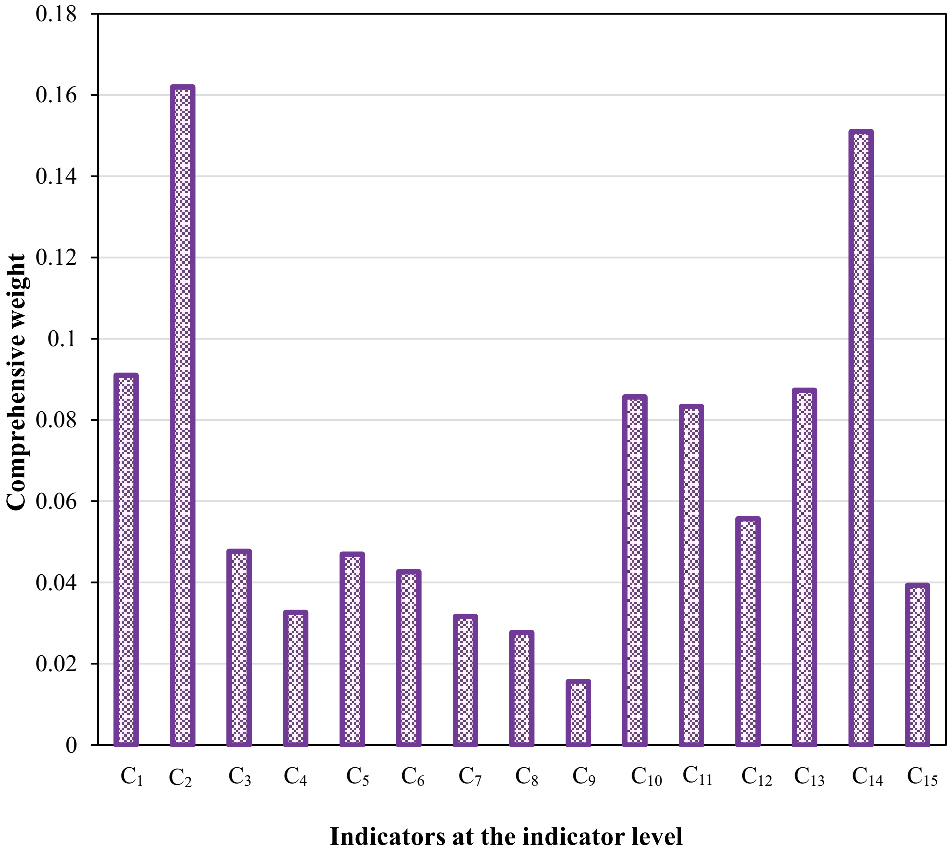

Fig. 2. Weight distribution of secondary indicators (local funds and unit investment (C_1); operating costs (C_2); construction area and service population ratio (C_3); sewage water volume (C_4); COD removal rate (C_5); BOD_5 removal rate (C_6); NH_4^+–N removal rate (C_7); SS removal rate (C_8); process applicability (C_9); stability of effluent reaching standard (C_{10}); ease of management and operation (C_{11}); malodorous gas influence (C_{12}); noise level (C_{13}); regional environmental temperature influence (C_{14}); impact on local residents (C_{15})).

Table 9
Indicator evaluation standard for a rural domestic sewage treatment model

Evaluation indicator	Rating				
	0.2	0.4	0.6	0.8	1.0
COD removal rate (%)	Worst (<60)	Worse (60–70)	Average (70–80)	Better (80–90)	Good (>90)
BOD_5 removal rate (%)	Worst (<60)	Worse (60–70)	Average (70–80)	Better (80–90)	Good (>90)
NH_4^+–N removal rate (%)	Worst (<60)	Worse (60–70)	Average (70–80)	Better (80–90)	Good (>90)
SS removal rate (%)	Worst (<60)	Worse (60–70)	Average (70–80)	Better (80–90)	Good (>90)
Process applicability	Worst	Worse	Average	Better	Good
Stability of effluent reaching standard	Worst	Worse	Average	Better	Good
Ease of management and operation	Difficult	Harder	Average	Simpler	Easy
Malodorous gas influence	Malodorous	Smelly	Smellable	Light smell	Odorless
Noise level	Noisy	Noisier	Average	Quiet	Extremely quiet
Regional environmental temperature influence	Serious	Obviously	Influential	Slightly	No
Impact on local residents	Serious	Obviously	Influential	Slightly	No

The comprehensive weights of the evaluation indicator system of rural domestic sewage treatment models in the cold northeast area determined by the AHP method are set:

W = {0.091, 0.162, 0.048, 0.033, 0.047, 0.043, 0.032, 0.028, 0.016, 0.086, 0.083, 0.056, 0.087, 0.151, 0.039}.

3.8. FCE method for the calculation result of the evaluation value

Each indicator value was obtained through the FCE method. The standardized evaluation value R_L of each evaluation mode indicator is obtained through the scoring

Table 10
Classification of applicability evaluation system of rural domestic sewage treatment model

Classification	Various indicators
Qualitative indicators	Process applicability (C_9); stability of effluent reaching standard (C_{10}); ease of management and operation (C_{11}); malodorous gas influence (C_{12}); noise level (C_{13}); regional environmental temperature influence (C_{14}); impact on local residents (C_{15})
Quantitative indicators	Local funds and unit investment (C_1); operating costs (C_2); construction area and service population ratio (C_3); sewage water volume (C_4); COD removal rate (C_5); BOD_5 removal rate (C_6); NH_4^+–N removal rate (C_7); SS removal rate (C_8)

standard of each indicator. Then, the weight set W and the indicator evaluation result R_L are multiplied and added. Finally, the final score of each evaluation mode is determined by calculation, and the fuzzy measurement results are obtained. The fuzzy measurement results are shown in Table 11. The fuzzy integral evaluation model is used to calculate the evaluation value and the calculation result is obtained.

3.8.1. Calculation result of the evaluation value of indicator layer

The evaluation value calculation of A_1 indicator (economic benefit) of V_1 includes 4 indicator levels under B, and their membership degrees are 0.901, 0.965, 1.000, 0.913, and the order of membership is $B_2 > B_1 > B_3 > B_4$. The corresponding fuzzy measures are 0.318, 0.301, 0.277, and 0.104. According to the fuzzy integral evaluation model (Eq. (9)), the evaluation value $L_1^1 = 0.955$ is calculated. Similarly, $L_1^2 = 0.978$, $L_1^3 = 0.985$, and $L_1^4 = 0.882$ can be calculated.

3.8.2. Calculation result of the evaluation value of criterion layer

Taking the evaluation value of each indicator of the indicator layer as the degree of membership, the comprehensive evaluation value of V_1 is calculated according to the integral model of the FCE $L_0^1 = 5.128$, the same method is calculated $L_0^2 = 4.973$, $L_0^3 = 5.026$.

3.9. Use weights to judge and calculate the pros and cons of governance models

The indicator weights of the AHP method are used to judge the advantages and disadvantages of the three governance models, centralized governance, decentralized governance, and water-sensitive area governance, respectively, and perform their weight addition and calculation.

Local funds and unit investment (C_1), operating costs (C_2), construction area and service population ratio (C_3), sewage water volume (C_4), COD removal rate (C_5), BOD_5 removal rate (C_6), NH_4^+–N removal rate (C_7), SS removal rate (C_8), process applicability (C_9), stability of effluent reaching standard (C_{10}), ease of management and operation (C_{11}), malodorous gas influence (C_{12}), noise level (C_{13}), regional environmental temperature influence (C_{14}), impact on local residents (C_{15}). Following a literature review and practical application, the study weight and rank the three governance models and each typical governance technology, and then select the best solution.

3.9.1. Centralized governance model advantage indicator weight calculation results

Biological contact oxidation method, sequencing batch reactor activated sludge process, membrane bioreactor, CRI system, and constructed wetland treatment technology are respectively G_1, G_2, G_3, G_4, and G_5. The calculation results are shown in Table 12. Through the calculation of the comprehensive weight result of the AHP method, the comprehensive evaluation result of $G_2 = 0.820$ is the highest, $G_1 = 0.375$, $G_3 = 0.308$, $G_4 = 0.701$, and $G_5 = 0.483$. $G_2 > G_4 > G_5 > G_1 > G_4$. The calculation results show that SBR governance technology is the best choice for a centralized governance model.

3.9.2. Decentralized governance model advantage indicator weight calculation results

Small constructed wetland, soil infiltration technology, stable pond technology, and septic tank technology are respectively G_6, G_7, G_8, and G_9. The calculation results are shown in Table 13. Through the calculation of the comprehensive weight result of the AHP method, the comprehensive evaluation result of $G_7 = 0.803$ is the highest, $G_8 = 0.585$, $G_6 = 0.537$, and $G_9 = 0.431$. $G_7 > G_8 > G_6 > G_9$. The calculation results show that soil infiltration technology is the best choice for decentralized governance.

3.9.3. Treatment of water environment sensitive areas advantage indicator weight calculation results

Constructed wetland treatment technology, septic tank technology oxidation pond technology and are respectively G_{10}, G_{11}, and G_{12}. The calculation results are shown in Table 14. Through the calculation of the comprehensive weight result of the AHP method, the comprehensive evaluation result of $G_{10} = 0.787$ is the highest, $G_{11} = 0.585$, $G_{12} = 0.470$. $G_{10} > G_{11} > G_{12}$. The calculation results show that the constructed wetland technology is the best choice for the treatment model of water environment sensitive areas.

3.10. Weighted results and important weights

According to Table 8, the weights of the first-level indicators, namely the indicator layer, are 0.540, 0.163, and 0.297, respectively. The economic benefits are the highest,

Table 11
Fuzzy measurement results of criterion level and indicator level

Criterion layer	Indicator layer	Fuzzy measure
Economic benefits (B_1)		0.401
	Local funds and unit investment (C_1)	0.301
	Operating costs (C_2)	0.318
	Construction area and Service population ratio (C_3)	0.277
	Sewage water volume (C_4)	0.104
Technical performance (B_2)		0.279
	COD removal rate (C_5)	0.135
	BOD_5 removal rate (C_6)	0.123
	NH_4^+–N removal rate (C_7)	0.111
	SS removal rate (C_8)	0.112
	Process applicability (C_9)	0.103
	Stability of effluent reaching standard (C_{10})	0.225
	Ease of management and operation (C_{11})	0.191
Environmental impact (B_3)		0.313
	Malodorous gas influence (C_{12})	0.282
	Noise level (C_{13})	0.294
	Regional environmental temperature influence (C_{14})	0.377
	Impact on local residents (C_{15})	0.047

Table 12
Centralized governance technical advantage indicator calculation

Evaluation indicator	Comprehensive weight	Governance technology				
		G_1	G_2	G_3	G_4	G_5
C_1	0.091	–	√	–	√	√
C_2	0.162	–	√	–	√	–
C_3	0.048	–	√	–	–	√
C_4	0.033	–	√	–	√	–
C_5	0.047	√	√	√	√	√
C_6	0.043	√	√	√	√	√
C_7	0.032	√	√	√	√	√
C_8	0.028	√	√	√	√	√
C_9	0.016	–	√	√	–	√
C_{10}	0.086	√	√	√	–	–
C_{11}	0.083	√	√	–	√	√
C_{12}	0.056	√	–	√	√	√
C_{13}	0.087	–	–	–	√	–
C_{14}	0.151	–	√	–	–	–
C_{15}	0.039	–	–	–	√	√
Calculation results		0.375	0.820	0.308	0.701	0.483

accounting for more than 50%. Therefore, after actual investigation and literature reference, economic efficiency is the primary consideration, followed by environmental impact, and finally is technical performance. According to Fig. 2, the overall weight of the operating cost budget in the secondary indicator is 0.161. In the selection of rural domestic sewage treatment models in the cold northeast region, the indicator of operating cost budget is the most important. The weights of the five indicators are 0.151, 0.091, 0.087, 0.086, and 0.083 respectively, including regional environmental temperature impact, local capital and unit investment, noise level, stability of effluent reaching the standard, and ease of management and operation. It is a relatively important indicator for the applicability evaluation of the rural domestic sewage treatment model in the cold northeast area. The weights of the above six indicators add up to 0.609,

Table 13
Decentralized governance technical advantage indicator calculation

Evaluation indicator	Comprehensive weight	Governance technology			
		G_6	G_7	G_8	G_9
C_1	0.091	–	√	√	√
C_2	0.162	√	√	√	√
C_3	0.048	–	–	–	–
C_4	0.033	–	√	–	–
C_5	0.047	√	√	√	√
C_6	0.043	√	√	√	–
C_7	0.032	√	√	√	–
C_8	0.028	√	√	√	√
C_9	0.016	–	√	–	√
C_{10}	0.086	√	√	–	–
C_{11}	0.083	√	√	–	–
C_{12}	0.056	√	√	√	–
C_{13}	0.087	–	√	√	√
C_{14}	0.151	–	–	–	–
C_{15}	0.039	–	√	√	–
Calculation results		0.537	0.803	0.585	0.431

Table 14
Treatment of water environment sensitive areas advantage indicator calculation

Evaluation indicator	Comprehensive weight	Governance technology		
		G_{10}	G_{11}	G_{12}
C_1	0.091	√	√	√
C_2	0.162	√	√	√
C_3	0.048	—	—	—
C_4	0.033	√	—	—
C_5	0.047	√	√	√
C_6	0.043	√	√	—
C_7	0.032	√	√	—
C_8	0.028	√	√	√
C_9	0.016	—	—	√
C_{10}	0.086	√	—	—
C_{11}	0.083	√	—	—
C_{12}	0.056	√	√	—
C_{13}	0.087	√	√	√
C_{14}	0.151	—	—	—
C_{15}	0.039	√	√	√
Calculation results		0.787	0.585	0.470

accounting for more than three-fifths of the total indicators. These indicators should be focused on in practical applications.

4. Discussion

The important indicators selected based on the basic conditions and principles constructed by the comprehensive evaluation indicator system for rural domestic sewage treatment models above can clearly indicate whether the treatment process is in line with the operation of the area. The indicator system can more comprehensively reflect the actual operating efficiency of rural domestic sewage treatment facilities, and it is also conducive to a better and accurate selection of the actual environmental impact [9]. Through the FCE method to verify the ranking of 18 indicators, the ultimate goal is to develop a comprehensive and sustainable system for evaluating WWTFs, but it is uncertain and imprecise [17]. The AHP and FCE methods are combined, using mathematical methods to transform human subjective judgments into comparable indicators, scientifically sorting elements, and then substituting mathematical methods into fuzzy phenomena to become more flexible. Use this combination method to optimize the relevant processes of the three governance models.

4.1. Analysis of centralized governance model

The centralized management model of rural domestic sewage treatment in CRNC is suitable for rural areas where the population of a single village is concentrated or multiple villages are connected. The distance from the municipal drainage pipe network is relatively short [18]. When chooses a centralized treatment model, the SBR process is preferred. Based on the above calculation result, G_2 has the highest score, which is 0.820. So SBR treatment process is preferred. The process meets the above comprehensive evaluation indicators of C_1–C_{11} and C_{14}, especially because C_1 = 0.091, C_2 = 0.162, C_{10} = 0.086, C_{11} = 0.083, C_{13} = 0.087, and C_{14} = 0.151 conform to the process. The intermittent activated sludge method is an activated sludge wastewater treatment technology that operates according to the intermittent aeration method, also called the sequential batch activated sludge method. The main body of the SBR process is an aeration tank, in which the sewage inlet, stirring and aeration, standing precipitation, water outlet, and idle stages are completed in sequence. The treatment method has the advantages of simple process, low cost, flexible operation mode, good denitrification and phosphorus removal effect, good stability of treatment effluent up to the standard, simple process, and low operating cost. Through the research, Ju et al. [20] showed that for the treatment of domestic sewage in rural China, it is necessary to follow the appropriate treatment process, long-term operation management, and reasonable planning with the guaranteed operation of funds [19]. Based on the AHP, relying on the Delphi method (DM) and the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method to select the best processing technology [20]. It is easy to reach a consensus in the DM, but subjective judgment has a greater influence [20]. Calculated by this method, the operating budget is the most important indicator, and the process meets the primary considerations. The management and operation difficulty indicator is a relatively important evaluation indicator, and the selected process of this governance model is also in line with the target. After the construction of the sewage treatment plant, the influence of the regional environmental temperature in the relatively important indicator was avoided. In addition, the quality of nitrogen and phosphorus removal, sewage treatment, and effluent water quality are good, which are all relatively important five indicators and have good performance.

The SBR wastewater treatment process performs well in the centralized treatment of urban sewage and rural sewage, and it is widely used. The process can also be applied to various automatic control systems at the same time [21]. However, the rural landforms are complex and random. The SBR wastewater treatment process can be combined with the CRI treatment process. The studies have shown that the artificial rapid infiltration technology can also achieve better treatment effects in terms of removing organic pollutants and TP and TN in terms of cost, and the combined process can be used to treat sewage in the Chaohu Lake Basin [22]. The advantages of the combination of the two are not restricted by site conditions, occupies a small area, the system has a high hydraulic load, does not pollute groundwater, the infiltration medium can be flexibly adjusted, and the investment cost and energy consumption are low. It can supplement the site restriction of the SBR treatment process. The operation is simple. The technical level of the required management personnel is not high, and it is in line with the important and relatively important indicators of the secondary weight indicators [23].

4.2. Analysis of decentralized governance model

The decentralized governance model is suitable for rural areas with complex topography, small population, scattered living areas, and difficulty in laying drainage pipe networks. The local natural and ecological conditions have a negative impact on the selected treatment process and treatment technology. This model divides the scattered residents of a larger area into smaller areas to treat domestic sewage by means of on-site treatment [24]. To choose a decentralized treatment model for rural domestic sewage, recommend the soil infiltration technology. The soil infiltration technology is suitable for the treatment of dispersed domestic sewage. The effluent quality is better under the action of soil-microbes-plants through surface tension and aerobic filtration layer [25]. Based on the above calculation results, G_7 has the highest calculation score, which is 0.803, so soil infiltration technology is preferred. The process meets the above comprehensive evaluation indicators of C_1–C_2, C_4–C_{13}, and C_{15}, especially because C_1 = 0.091, C_2 = 0.162, C_{10} = 0.086, C_{11} = 0.083, and C_{13} = 0.087 conform to the process. The combination of the septic tank and sand filter is a feasible technology for a decentralized governance model, mainly in rural areas. The wastewater produced can be reused. By comparing the two decentralized governance models designed to produce A($^+$) circulating water in Southeast Queensland, the stability of their shock loads, energy consumption, and short-term greenhouse gas emissions were evaluated. Compared with this technology, the stability of the nitrification process in MBR will be affected by the total nitrogen load [26]. For energy consumption, the unit energy consumption of the MBR system is much higher than other distributed aerobic biological filter systems [25]. The one-time input cost is low, and it is pointed out that although MBR has a good removal effect, the equipment cost is high, and the high management cost is not applicable for China's decentralized rural sewage treatment [27].

The decentralized management model can be used in CRNC to use multilevel soil infiltration technology. The climate has a certain influence on the stabilization pond technology, but the stabilization pond has a certain processing capacity and can be used as an auxiliary process [28]. Through the research on slurry wastewater treatment in Lulong County, Northeast Hebei, China, the composite construction of stabilization pond and artificial treatment technology has low cost, good effect, and is suitable for rural areas to adapt to local conditions [29]. So soil infiltration *in-situ* collection technology and stable pond technology for joint treatment. Fertile soil in CRNC and good soil characteristics should be combined with the personnel and operating costs of the treatment area to improve the relevant use system. According to the actual situation, decision-makers implement relevant technologies to realize the integration of sewage treatment and actual conditions.

4.3. Analysis on governance model of water environment sensitive area

In the selection of water environment sensitive areas for rural domestic sewage in CRNC, various water-sensitive areas are used such as scenic spots, drinking water sources, and nature reserves. This governance model is to repair the imbalance caused by the damage of regional water bodies by external and internal factors. For the selection of the process of treating rural domestic sewage in CRNC in the water environment sensitive area, the treatment method of constructed wetland technology is preferred. Based on the above calculation results, the G_{10} calculation score is the highest, which is 0.787, so the constructed wetland technology method is preferred. At the same time, the process meets the above comprehensive evaluation indicators of C_1–C_2, C_4–C_8, C_{10}–C_{13}, C_{15}, because C_1 = 0.091, C_2 = 0.162, C_{10} = 0.086, C_{11} = 0.083, and C_{13} = 0.087. According to the evaluation indicator calculation, the constructed wetland technology meets the requirements. The constructed wetland has the advantages of synchronous and automatic sludge treatment and the formation of ecological landscapes [30]. The constructed wetland technology uses the natural ecological management system in which the seepage surface of the soil is similar to the ground and continuously purifies the substrate, plants, and microorganisms together. Constructed wetlands have the advantages of low investment and construction funds, low operating costs, fewer operators, less energy consumption, simultaneous automatic sludge treatment, and formation of ecological landscapes [30]. For scenic spots, drinking water sources, and nature reserves, the advantages are obvious, and the governance model is desirable. For the secondary indicators of the comprehensive weight results, local funds and unit investment, operating cost budget, management, and operation difficulty are in good compliance with the three indicators. At the same time, it has the characteristics of additional landscape generation, which is good for the governance of water-sensitive areas in Northeast China.

Due to the mechanism of pollution removal of constructed wetland, including adsorption, filtration, precipitation, redox, microbial metabolism, plant transpiration, and the role of various organisms [31]. In the selection of the treatment model, this research took into account the temperature changes in Northeast China. Greenhouses can be built to increase the temperature impact in autumn, winter, and spring, and ensure the efficiency and effectiveness of wastewater treatment. It is also possible to select constructed wetland as the core process, supplemented by other processes for joint treatment to achieve the effect of improving the quality of the effluent. The combined process of constructed wetland was used in the sewage treatment of Hetou Village, Xingan County, China to ensure that the sewage was discharged up to the standard [32]. With the acceleration of urbanization and the gradual decrease of the agricultural population, many rural areas no longer use manure as a material, and environmental pollution caused by the overflow of manure and sewage has gradually become prominent. The "constructed wetland and septic tank" combined technology process solves such problems well. At the same time, this technology has the advantages of low cost, simple operation, stable operation, good water quality, and good environmental benefits. It belongs to unpowered sewage treatment. It is a choice of treatment mode that meets the actual conditions of rural areas in the Northeast of China.

Through the analysis of CRNC's rural domestic sewage treatment mode, it provides solutions and options for the treatment of rural domestic sewage in concentrated, decentralized, and water-sensitive areas under low-temperature environments, and provides decisions for the treatment of domestic sewage in cold areas, low temperatures, different population sizes, and distribution villages [33]. The author provides a certain reference value. The research has certain application prospects for selecting wastewater treatment programs based on local conditions and considering multiple factors [34].

5. Conclusions

This research proposes three governance models of centralized governance model, decentralized governance model, and water environment sensitive area governance model based on the characteristics of rural domestic sewage treatment in CRNC. Using the combination of AHP and FCE methods, various indicators of domestic sewage treatment were calculated. Calculate the three criterion-level indicator weights of rural domestic sewage and 15 small indicators under each indicator, finally, calculate the comprehensive weights and then analyze the weight distribution of the secondary indicators to determine the evaluation criteria. Based on the model analysis and calculation results, it is recommended to use SBR and CRI combined treatment technology for centralized treatment mode, soil infiltration technology, and stable pond technology for decentralized treatment mode, and constructed wetland treatment technology for water environment sensitive areas. Based on the analysis of the treatment model of rural domestic sewage in CRNC, this work provides solutions and choices for the treatment of rural domestic sewage in areas with relatively low-temperature environments, and provides certain valuable information for reference for all decision-makers.

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