frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 13 February 2023
DOI 10.3389/fenvs.2023.1112689

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Water and Wastewater Management, a section of the journal Frontiers in Environmental Science

RECEIVED 30 November 2022
ACCEPTED 30 January 2023
PUBLISHED 13 February 2023

CITATION
Wu S, Chai Q, Liu X and He B-J (2023), Sustainability assessment of rural toilet technology based on the unascertained measure theory.
Front. Environ. Sci. 11:1112689.
doi: 10.3389/fenvs.2023.1112689

Sustainability assessment of rural toilet technology based on the unascertained measure theory

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Upgrading toilets in rural areas is an effective way to protect public health and reduce environmental pollution. Although there are studies on rural toilets, the sustainable performance of rural toilets in developing areas is considerably less understood. The study aims to build a sustainability assessment model of rural toilet technology to support the local government in upgrading rural toilets. The unascertained measure theory is integrated into the model to quantify the sustainability performance of rural toilet technology in three dimensions: economy, service and management, and environment. A case study of Honghai Village, Inner Mongolia, China, is conducted to verify the reliability of the sustainability assessment model. The results indicate that the sustainability performance of the three-compartment septic tank toilet technology is good in Honghai Village. The results are consistent with the situation of the three-compartment septic tank toilets in the village, which verifies the model's validity. This study can help local government significantly upgrade rural toilets and improve the living standards of rural residents.

KEYWORDS

rural toilet, separate toilet, sustainability assessment, unascertained measure theory, case study

1 Introduction

Toilets are essential to human wellbeing. However, according to the United Nations, at least 892 million people currently practice open defecation, most living in rural areas (United Nations, 2022). And many rural residents use toilets that cannot properly treat human waste. In China, 45% of the human waste produced by rural households is not properly treated, 79% of which is used as fertilizer and 12% is discharged directly into the environment (Zhou et al., 2022). Lack of toilets and inadequate toilet treatment capacity contribute to an increasing risk of transmission of infectious diseases and induce poverty (Akaishi et al., 2021; Dancer et al., 2021). More than 3,60,000 children die yearly from water and sanitation-related diarrheal diseases (Ignacio et al., 2018). In order to reduce the health and environmental threats posed by human waste, many governments have tried to upgrade the toilets in rural areas. The Chinese government has implemented a "toilet revolution" policy since 2015, working to improve toilets in rural areas (Cheng et al., 2018).

To guide the upgrading of toilets, the researchers have conducted studies on toilet technology assessment. Liu et al. (2021) focused on the microbial safety and antibiotic resistance of using open composting toilets and green composting toilets. In the Philippines, Zakaria et al. (2018) evaluated the service capacity of smart toilets. They found the smart toilets can monitor usage data for immediate maintenance and can save 97% of water usage compared to conventional toilets. Hill et al. (2013)

argued the reliability of the urine-diverting vermicomposting toilets by adopting the Solvita compost stability and maturity test. In Hong Kong, Liu et al. (2019) focused on the environmental impacts of the seawater toilet flushing (SWTF) system. They compared the environmental performance of five types of toilets using life cycle assessment (LCA). The result revealed that SWFT systems have excellent environmental performance, and can significantly reduce CO_2 emissions. Some studies have discussed the performance of toilet technology from both an economic and environmental perspective. Devkota et al. (2015) evaluated the environmental and economic performance of rainwater flushing toilets using LCA. The results showed that rain-flush toilets could significantly reduce energy consumption and greenhouse gas emissions. Anand and Apul (2011) evaluated the economic and environmental performance of potable water-flushed toilets, rain-flushed toilets, and composting toilets. The results indicated that rain-flushed and composting toilets are more efficient in saving energy and reducing CO_2 emissions. Shi et al. used cost-benefit analysis and LCA to analyze the economic and environmental performance of resource-oriented toilets and conventional toilets. The results suggested that resource-oriented toilets are better suited for rural use than traditional toilets in terms of cost, energy, and resources. Gao et al. (2017) used the economic net present value method to analyze the energy consumption and greenhouse gas emission impacts of rural toilet systems under five scenarios. Zhu et al. (2021) used the analytic hierarchy process (AHP) and LCA to construct an evaluation index system for public toilet technology in terms of economic, social, and environmental benefits. The correlational studies have focused more on the economic, technical and environmental performance of toilets (Gao et al., 2017; Fu et al., 2022; Tembhurkar et al., 2022; Fu et al., 2023). Few studies have considered the impact of residents when focusing on the sustainable performance of rural toilets. Unlike urban areas, rural residents are more deeply involved in the construction, management and maintenance of private toilets. The sustainable benefits of rural toilet technology can only be realized when the toilets can be accepted and maintained by rural residents. Accordingly, this study aims to construct an assessment model that reveals the sustainability performance of toilet technology in rural areas. The research objectives include: 1) Build sustainability assessment indexes of rural toilet technology; 2) Establish the sustainability assessment model of rural toilet technology; 3) A case was used to verify the effectiveness of the sustainability assessment model of rural toilet technology.

The remainder of the paper is structured as follows. Section 2 builds the sustainability assessment index system for rural toilet technology; Section 3 introduces the research methodology and constructs rural toilet technology sustainability assessment model (RTTSAM) based on unascertained measure theory (UMT); Section 4 shows the results of sustainability assessment of rural toilet technology in the case study and discusses the main findings; Section 5 includes the conclusion and the implication of the study.

2 Material and methods

2.1 Establishment of the sustainability assessment indexes for rural toilet technology

2.1.1 Establishment of sustainability assessment indexes

Through literature review and site survey in rural areas, a total of 16 indexes were finally obtained (Devkota et al., 2015; Gao et al., 2017; Shi et al., 2018; Zhu et al., 2021). These indexes were divided into three dimensions: economy, service and management, and environment (Table 1). Among them, five indexes belong to economic dimension, 6 indexes belong to service and management dimension, and 5 indexes belong to service and management dimension.

TABLE 1 Index grading standards.

Grade	Grade I	Grade II	Grade III	Grade IV	Grade V
Situation	Very high	High	Average	Low	Very low
Standard	(9.0, 10)	(8.0, 9.0)	(7.0, 8.0)	(6.0, 7.0)	(0, 6.0)

The economic dimension covers the indexes related to the costs of toilet upgrading. The construction cost index and the equipment cost index focus on the cost of the toilets. The ancillary facility cost index refers to the cost of supporting equipment required for the operation, such as the cost of water supply pipes, sewage pipes, etc. The operation and maintenance cost index cover the costs incurred for the use and maintenance of toilets. The policy support index focuses on the impact of the support policies on the cost of toilet upgrading.

The services and management dimension focus on the service performance of the toilets and the maintenance needs of the toilets. The treatment effect index and treatment capacity index reflect the capacity of the toilet to treat human waste. The convenience index, safety index, and durability index refer to the quality of toilet services. Besides, the operation and maintenance requirement index measures the intensity of toilet operation and maintenance requirements.

The environmental dimension refers to the impact of toilet technology on the environment. Since the treated human waste can be used as fertilizer, it can reduce the environmental impact of human waste while providing economic benefits to rural residents. Therefore, the study uses the waste reuse index to reflect the ability of toilet technology to reuse human waste. The water conservation index measures the ability of toilet technology to save water. The performance of toilets is critical for rural residents with inadequate water supply systems or in arid areas. The energy conservation index, noise control index, and odor control index measure the impact of toilets on energy, noise, and odor, respectively. The sustainability assessment indexes of rural toilet technology are shown in Figure 1.

2.1.2 Determination of the index grading standards

This study determines the index grading standards through literature review and consulting experts. They are divided into five grades. The assessment grading space is $G = \{G_1, G_2, G_3, G_4, G_5\}$. The specific classification standards are shown in Table 1.

2.2 Establishment of the RTTSAM

2.2.1 Unascertained measure theory

The UMT is an uncertainty information theory proposed by Wang (1990). It can quantitatively analyze uncertainty factors effectively and reliably. There is uncertainty in evaluating sustainability indexes for rural toilet technology due to subjective perception of experts (Xing et al., 2022). Therefore, the study adopts the UMT to establish a sustainability assessment model of rural toilet technology.

Suppose that the assessment object $T = \{T_1, T_2, \cdots, T_n\}$, each assessment object has m assessment indexes, and the assessment index $V = \{V_1, V_2, \cdots, V_m\}$. If t_{ij} represents the measured value of

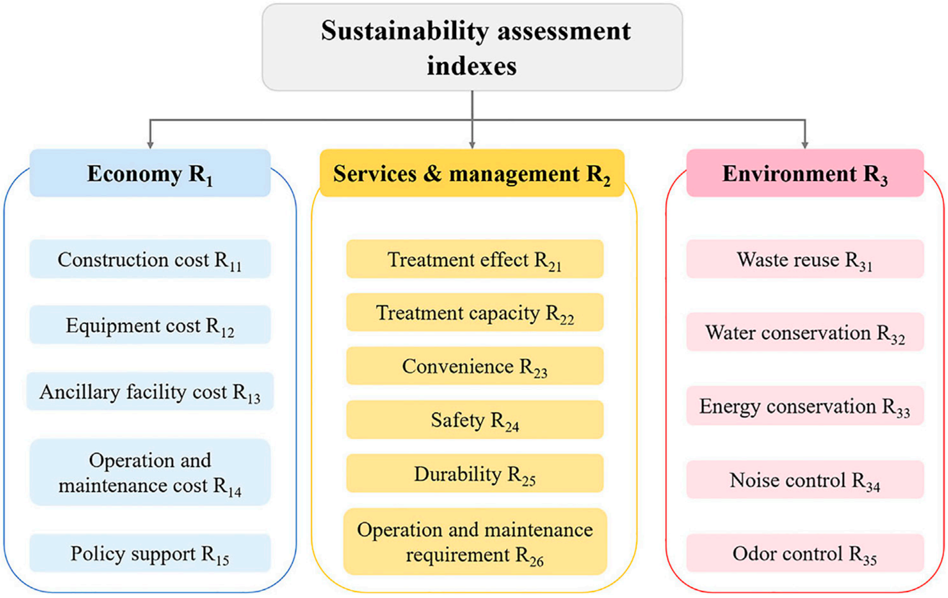


FIGURE 1
Sustainability assessment indexes of the rural toilet technology.

the i-th assessment object T_i for the j-th assessment index V_j, then T_i can be expressed as an m-dimensional vector $T_i = (t_{i1}, t_{i2}, \cdots, t_{im})$. Suppose that the assessment grade space $G = \{G_1, G_2, \cdots, G_P\}$, where G_k is the rating value of T_{ij}. If the k-th grade is higher than the $k+1$-th grade in the sustainability assessment process, it is denoted as $G_k > G_{k+1}$. If $G_1 > G_2 > \cdots > G_p$ or $G_1 < G_2 < \cdots < G_p$ is satisfied, then $G = \{G_1, G_2, \cdots, G_P\}$ is an ordered segmentation class of assessment space G.

2.2.2 Single-index unascertained measure

If $\mu_{ijk} = \mu(t_{ij} \in G_k)$ represents the degree to which the measured value t_{ij} belongs to the k-th assessment grade G_k, then

$$0 \le \mu\left(t_{ij} \in G_k\right) \le 1 \left(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m; k = 1, 2, \cdots, p;\right) \quad (1)$$

$$\mu\left(t_{ij} \in G_k\right) = 1 \left(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m\right) \quad (2)$$

$$\mu\left|t_{ij} \in \bigcup_{l=1}^{k} G_k\right| = \sum_{l=1}^{k} \mu\left(t_{ij} \in G_l\right) \ (k = 1, 2, \cdots, p) \quad (3)$$

Equation 1 is called "unboundedness," Eq. 2 is "normalization", and Eq. 3 is "additivity." If μ satisfies the Eqs 1–3, then μ is called the unascertained measure. In general, the construction methods of single index measure functions include linear, exponential, parabolic, and sinusoidal. And the restriction conditions of Eqs 1–3 must be satisfied.

Based on the single-index measure function $(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m; k = 1, 2, \cdots, p)$, the measured value μ_{ijk} of each index of the assessment object T_i can be obtained, and $(\mu_{ijk})_{m\times p}$ is defined the single-index measure matrix as follows:

$$\left(\mu_{ijk}\right)_{m\times p} = \begin{bmatrix} \mu_{i11} & \mu_{i12} \cdots & \mu_{i1p} \\ \mu_{i21} & \mu_{i22} \cdots & \mu_{i2p} \\ \vdots & \vdots \quad \ddots & \vdots \\ \mu_{im1} & \mu_{im2} \cdots & \mu_{imp} \end{bmatrix} \quad (4)$$

Based on the definition of the single-index measure function and the index grading standards in Table 1, the single-index unascertained measure function is determined. The function studied in this paper is linear, and the single-index unascertained measure function is made as follows:

$$\mu_{ij1} = \begin{cases} 0 & x_{ij} \le 8.5 \\ \dfrac{x_{ij} - 8.5}{1.0}, & 8.5 < x_{ij} \le 9.5 \\ 1 & x_{ij} > 9.5 \end{cases} \quad (5)$$

$$\mu_{ij2} = \begin{cases} 0 & x_{ij} \le 7.5 \text{ or } x_{ij} > 9.5 \\ \dfrac{x_{ij} - 7.5}{1.0}, & 7.5 < x_{ij} \le 8.5 \\ \dfrac{9.5 - x_{ij}}{1.0} & 8.5 < x_{ij} \le 9.5 \end{cases} \quad (6)$$

$$\mu_{ij3} = \begin{cases} 0 & x_{ij} \le 6.5 \text{ or } x_{ij} > 8.5 \\ \dfrac{x_{ij} - 6.5}{1.0}, & 6.5 < x_{ij} \le 7.5 \\ \dfrac{8.5 - x_{ij}}{1.0} & 7.5 < x_{ij} \le 8.5 \end{cases} \quad (7)$$

$$\mu_{ij4} = \begin{cases} 0 & x_{ij} \le 3.0 \text{ or } x_{ij} > 7.5 \\ \dfrac{x_{ij} - 3.0}{1.0}, & 3.5 < x_{ij} \le 6.5 \\ \dfrac{7.5 - x_{ij}}{1.0} & 6.5 < x_{ij} \le 7.5 \end{cases} \quad (8)$$

$$\mu_{ij5} = \begin{cases} 1 & x_{ij} \le 3.0 \\ \dfrac{x_{ij} - 3.0}{1.0}, & 3.0 < x_{ij} \le 6.5 \\ 0 & x_{ij} \ge 6.5 \end{cases} \quad (9)$$

Based on Eqs 5–9, the single-index unascertained measure function is expressed graphically, as shown in Figure 2.

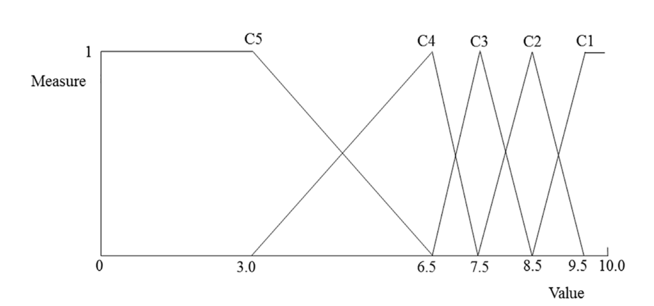


FIGURE 2
The single-index unascertained measure function.

2.2.3 Determination of indexes weights by AHP method

Analytic Hierarchy Process (AHP) method is proposed by Satty et al. and can solve complex multi-objective and multi-criteria decision problems using less quantitative information (Saaty, 1980). This study used the AHP approach to determine the index weight. The specific steps of AHP approach to determine the index weight are as follows.

(1) Establishment of the hierarchical structure.

The hierarchical structure of sustainability assessment of rural toilet technology is shown in Figure 1.

(2) Construction of the judgment matrix.

The judgment matrix A is represented as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{10}$$

where a_{ij} refers to a qualified pairwise comparison for indexes of the same level. 1-9 point scale method was used to obtain the value of the a_{ij} (see Supplementary Schedule S1), thus where a_{ij} takes the values of 1-9, 1/2-1/9.

(3) Calculation the weight of indexes.
1) Normalized judgment matrix A

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \ (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \tag{11}$$

2) Add the normalized matrix by rows, then

$$w' = \sum_{j=1}^{n} a'_{ij} (i = 1, 2, \cdots n) \tag{12}$$

3) Normalizing the vectors $w' = (w'_1, w'_2, \cdots, w'_n)^T$,

$$w_i = \frac{w'_i}{\sum_{j=1}^{n} w'_j} \quad (i = 1, 2, \cdots n) \tag{13}$$

The obtained eigenvector is $w = (w_1, w_2, \cdots, w_n)^T$.

4) Calculating the largest eigenvalue of the judgment matrix $\lambda_{\max}$ with the Eq. 14

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} (Aw)_i}{nw_i} \tag{14}$$

where is the i-th element of the vector obtained by multiplying matrix A with weight vector w.

5) Calculating the consistency index (C.I.) with the Eq. 15.

$$\text{C.I.} = \frac{\lambda_{\max} - n}{n - 1} \tag{15}$$

where n is the number of the indexes in the judgment matrix.

6) Calculating the consistency ratio (C.R.) with the Eq. 16.

$$\text{C.R.} = \frac{\text{C.I.}}{\text{R.I.}} \tag{16}$$

where R.I. is the random index shown in Supplementary Schedule S2. If C.R. > 0 and C.R. < 0.1, judgment matrix A is considered to meet the requirements of the consistency check. Otherwise, the judgment matrix needs to be reconstructed.

1-9 point scale method is used to construct a judgment matrix for the first-level indexes and second-level indexes. Then the weights of the judgment matrix are obtained. And the consistency of the judgment matrix is checked. As is shown in Supplementary Schedule S3, the consistency check meets the corresponding requirements. The weights of the indexes are shown in Table 2.

2.2.4 Multi-index comprehensive unascertained measure

If μ_{ik} satisfies $0 \le \mu_{ik} \le 1, \mu_{ik} = \sum_{j=1}^{m} w_j \mu_{ijk} \, (k = 1, 2, \cdots, p)$, where w_j for the index weight, $(\mu_{ik})_{n \times p}$ represents the multi-index unascertained measure matrix.

$$(\mu_{ik})_{n \times p} = \begin{bmatrix} \mu_{11} & \mu_{12} & \cdots & \mu_{1p} \\ \mu_{21} & \mu_{22} & \cdots & \mu_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{n1} & \mu_{n2} & \cdots & \mu_{np} \end{bmatrix} \tag{17}$$

2.2.5 Confirmation of sustainability assessment grade

The credible degree recognition criteria is introduced to obtain the sustainability assessment grade. Suppose that λ is the credible degree ($\lambda \ge 0.5$, usually, $\lambda = 0.6$ or 0.7), if $G_1 > G_2 > \cdots > G_p$,

$$p_0 = \min \left| p: \sum_{k=1}^{p} \mu_{ik} > \lambda, i = 1, 2, \cdots, n \right| \tag{18}$$

2.3 Implementation steps of RTTSAM

The study used AHP method to calculate the weights of sustainability assessment indexes. Then, a sustainability assessment model of rural toilet technology was established based on unascertained measure theory. The flowchart of the research method is shown in Figure 3.

TABLE 2 Weights of sustainability assessment indexes.

First-level index	Weight	Second-level index	Weight	General weight
Economy R_1	0.364	Construction cost R_{11}	0.278	0.101
		Equipment cost R_{12}	0.234	0.085
		Ancillary facility cost R_{13}	0.213	0.078
		Operation and maintenance cost R_{14}	0.121	0.044
		Policy support R_{15}	0.153	0.056
Services and management R_2	0.284	Treatment effect R_{21}	0.188	0.054
		Treatment capacity R_{22}	0.143	0.041
		Convenience R_{23}	0.182	0.052
		Safety R_{24}	0.158	0.045
		Durability R_{25}	0.155	0.044
		Operation and maintenance requirement R_{26}	0.175	0.050
Environment R_3	0.352	Waste reuse R_{31}	0.252	0.089
		Water conservation R_{32}	0.244	0.086
		Energy conservation R_{33}	0.200	0.070
		Noise control R_{34}	0.139	0.049
		Odor control R_{35}	0.165	0.058

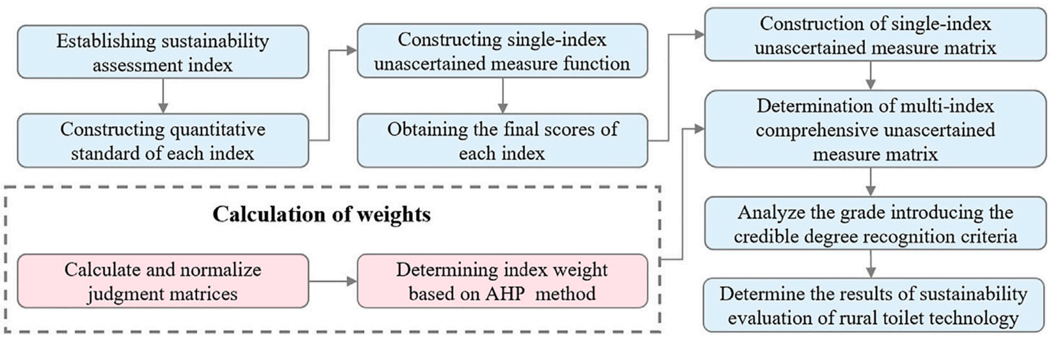


FIGURE 3
Flowchart of RTTSAM.

Step 1: Define the objects to be determined, and establish the sustainability assessment indexes and quantitative index grading standards.

Step 2: Construct the single-index unascertained measure function.

Step 3: Determine the single-index unascertained measure matrix.

Step 4: Calculate the weights of sustainability assessment indexes of rural toilets technology based on the AHP approach.

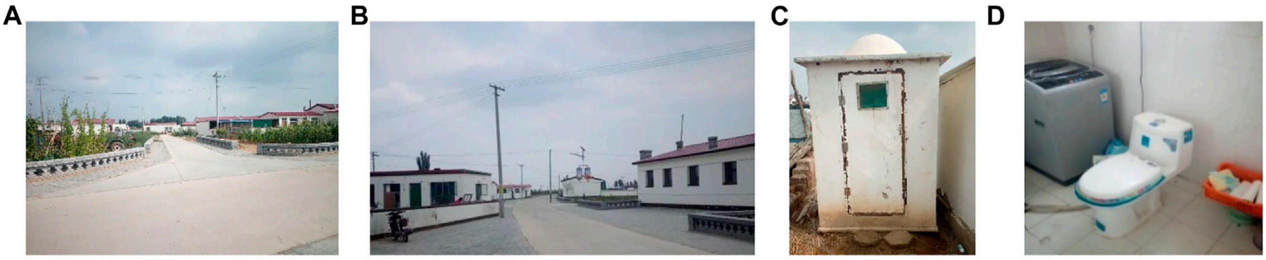
Step 5: Obtain the score of the sustainability assessment indexes of the assessment object.

Step 6: Determine multi-index comprehensive unascertained measure matrix.

Step 7: Introduce the credible degree recognition criteria to ensure the sustainability assessment grade of the assessment object.

2.4 Case study

The Honghai Village in Ordos, Inner Mongolia, China, was selected as a study area. The Honghai Village has a semi-arid continental climate. The minimum daily temperature in winter can be below −30°C in Honghai Village. The village has 1,384 inhabitants, mainly engaged in agriculture and animal



Village environment | Residential building | Outdoor toilet | Indoor toilet

FIGURE 4
Village, building and toilets.

TABLE 3 Basic information.

No.	1	2	3	4	5
Occupation	Professor	Village chief	Professor	Local Officers	Inspector
Working year	16	30	17	9	9
Education Level	Doctor	High school	Doctor	Undergraduate	Undergraduate
No.	6	7	8	9	
Occupation	Local Officers	Local Officers	Professor	Inspector	
Working year	10	15	18	10	
Education Level	Undergraduate	Undergraduate	Doctor	Undergraduate	

husbandry. After implementing the “toilet revolution” policy, the toilets in the village have been upgraded. There are two types of toilets in Honghai Village: indoor toilets and outdoor toilets. The toilets use three-compartment septic tanks to treat human waste. Three-compartment septic tank toilet (TCSTT) is a type of toilet that can treat manure in combination with a sewage treatment system. In areas where sanitation systems are unavailable, these toilets can also effectively treat human waste independently through anaerobic reaction and sedimentation (Tan et al., 2021). The treatment time for human waste in the three tanks is 20 days (first tank), 10 days (second tank), and 30 days (third tank). The solid-based manure in the third tank was a kind of slow release fertilizer. The situation of the village and toilets is shown in Figure 4.

The study invited experts, officers, and users to assess the sustainability of the TCSTT technology used in Honghai Village. The basic information of them is shown in Table 3. By calculating the average of the remaining scores after removing the highest and lowest scores, the final score of each sustainability assessment index was obtained in Supplementary Schedule S4.

3 Result and discussion

(1) Calculating the first-level index comprehensive unascertained measure matrix.

Based on the second-level index unascertained measure matrix (see Supplementary Schedule S5) and the weight of the second-level indexes, the first-level index comprehensive unascertained measure matrix can be calculated as follows:

$$\mu = \begin{bmatrix} 0.163 & 0.814 & 0.023 & 0.000 & 0.000 \\ 0.152 & 0.296 & 0.458 & 0.094 & 0.000 \\ 0.604 & 0.360 & 0.037 & 0.000 & 0.000 \end{bmatrix} \quad (19)$$

(2) Calculating the total target comprehensive measure matrix.

Based on the first-level index unascertained measure matrix and the weight of the first-level indexes, the total target comprehensive measure matrix can be calculated as follows:

$$\mu_{total} = [0.315\ 0.507\ 0.151\ 0.027\ 0.000] \quad (20)$$

(3) Credible degree recognition.

According to the credible degree recognition criteria, take the confidence $\lambda = 0.6$. According to Eq. 18, when $P_0 = 2$, $0.315 + 0.507 = 0.822 > 0.6$, and $0.027 + 0.151+0.507 = 0.685 > 0.6$. That is, the sustainability assessment grade of this toilet technology can be judged as grade II. The error is acceptable, and the assessment results are reliable. Similarly, the sustainability assessment grade of the indexes are shown in Table 4.

The assessment results show that the sustainability grade of TCSTT technology is grade II. From the perspective of three dimensions, TCSTT technology has the highest sustainability assessment grade in environment dimension with grade I, followed by economy dimension with grade II and services and management

TABLE 4 Sustainability assessment grade of each index.

First-level index	Grade	Second-level index	Grade	First-level index	Grade	Second-level index	Grade
R_1	II	R_{11}	II	R_2	III	R_{24}	II
		R_{12}	II			R_{25}	I
		R_{13}	II			R_{26}	II
		R_{14}	II	R_3	I	R_{31}	I
		R_{15}	II			R_{32}	I
R_2	III	R_{21}	III			R_{33}	I
		R_{22}	III			R_{34}	I
		R_{23}	II			R_{35}	II

dimension with grade III. When the sustainability level of the index is Grade III or lower, it is necessary to take steps to improve or replace the toilet technology. For villages located in nature reserves, water sources, and other villages with special needs, measures must be taken to upgrade or replace toilet technology for index with sustainability levels of grade II or lower. For indexes with a sustainability level of grade I, there is no need to improve them. The Honghai Village is not in a nature reserve, water source, or special needs. The sustainability level of TCSTTs has been able to meet the needs of Honghai Village. The results reveal that sustainability of the TCSTTs in the economic and environmental dimensions is acceptable. While the sustainability grade of services and management dimension is grade III. This means that TCSTTs need to improve the sustainability of the service and management dimensions.

Among the economical dimension, TCSTT technology shows high sustainability performance in the construction index (Grade II), equipment cost index (Grade II), and ancillary facility costs index (Grade II). The construction of TCSTTs is not complicated. The TCSTTs require only the addition of a three-compartment septic tank made of brick and concrete, as compared to the original toilets used by the rural residents. Otherwise, rural residents can purchase a finished three-compartment septic tank (Tan et al., 2021). The simple construction process of TCSTT can effectively save construction cost. The waste treatment equipment of TCSTT is available as either a finished three-compartment septic tank or can be made from concrete. In addition to septic tanks, rural residents only need to purchase a small number of equipment, such as pipes. Rural residents can choose different equipment options according to their financial situation. The equipment costs of TCSTT can be effectively controlled. Currently, there is no sanitation system in Honghai Village. Local residents want to upgrade the toilets first and then raise funds to build a sanitation system. The TCSTTs can treat human waste independently with low demand for supporting facilities. TCSTTs can also be in connection with sanitation facilities. For Honghai villages that lack sanitation facilities, TCSTTs can not only reduce the cost of ancillary facilities at present, but also can be used as a pretreatment process when sanitation facilities are installed (Singh et al., 2019). Overall TCSTTs are easy to build and low investment, which provides a good basis for the local residents to accept this kind of toilets (Acey et al., 2019). For rural households, the maintenance of TCSTT is simple and infrequent. Therefore, the sustainability level of operation and maintenance costs index is grade II. Another index with a sustainability level of grade II is the policy support index. To promote the toilet revolution policy, the local government has reimbursed part of the toilet construction costs and organized bulk purchases of appliances for residents. The village government is able to assist rural residents in purchasing toilet maintenance services. With the support of the government, the cost of toilets is reduced. The support of policy reduces the economic pressure on rural residents while increasing their willingness to use and maintain toilets (Poortvliet et al., 2018). In this way, the policy support improves the sustainability of TCSTTs. Overall, the sustainability performance of TCSTT's economic indexes is good.

For the services and management dimension, the sustainability level of the treatment effect index and treatment capacity index is Grade III. This means that it can meet the local standards for human waste treatment, but still needs further improvement. TCSTTs treat human waste through natural anaerobic fermentation. In order to improve the effluent treatment effect, the manure emptying time interval can be appropriately extended when the temperature is low. TCSTTs take about 30 days to treat human waste, which is suitable for household human waste treatment. When the number of families is large, the size of the septic tank should be increased appropriately, or the number of finished three-compartment septic tanks should be increased to reduce the treatment pressure (MARA, 2020). The sustainability level of the operation and maintenance requirement index of TCSTT is Grade II, which means that the residents can reliably manage and maintain the toilets. After being treated, the liquid flows out, the residue accumulates needs to be cleaned. But only the third septic tank need to be cleaned each time. The rest of the septic tank is forbidden from being cleaned due to insufficient treatment time (Tan et al., 2021). In winter, the connection pipes of TCSTT are prone to clogging due to the low temperature. Therefore, the management and maintenance frequency need to be increased in winter. Local governments need to enhance residents' awareness of TCSTT management and maintenance methods in order to effectively improve the effectiveness of TCSTT treatment (Junghanns and Beery, 2020). Since TCSTT technology mainly adopts natural anaerobic fermentation, it produces combustible gas during the treatment process, but the yield is small, and the safety is high. TCSTT technology can be used for both outdoor and indoor toilets. The convenience (Grade II) and safety (Grade II) of TCSTTs are ensured. The structure of TCSTT is relatively simple. The central part is built with concrete, steel, and other materials with good durability. Therefore, the durability of TCSTT is very high (Grade

I). In general, the TCSTT can meet the needs of rural residents and is easy to use and maintain.

TCSTT technology has outstanding environmental performance (Grade I). The human waste from the anaerobic fermentation of the TCSTT can be used as fertilizer and can reduce the cost of fertilizer (Liu et al., 2018). The residents of Honghai Village are accustomed to using human waste to fertilize their crops. The waste from TCSTT can be effectively reused (Grade I). Since TCSTT treats waste through natural anaerobic fermentation. Therefore, the treatment process of human waste requires less water (Grade I), less energy (Grade I), and no noise (Grade I). While the concrete three-compartment septic tank may emit an odor (Grade II) in the treatment process. Residents who choose concrete three-compartment septic tanks often build outdoor toilets to reduce the impact of odors, which can also make it easier for residents to get fertilizer. For residents using indoor toilets, flushing equipment with a finished three-compartment septic tank can effectively reduce the impact of odors. TCSTTs have been able to effectively reduce the environmental impact of human waste while providing benefits to agricultural production. The residents of Honghai Village are able to accept and use TCSTTs.

Traditionally, water flushing toilets are always considered as one with sanitation facilities (Gao et al., 2017). However, in rural areas that lack sanitation systems and need to reuse waste, the choice of TCSTTs applied in decentralised is more sustainable. The TCSTT technology shows high sustainability in Honghai Village. The TCSTTs are simple in structure, flexible in design, and easy to use. The TCSTT technology used in Honghai Village is economically acceptable to rural residents, easy to maintain, and can effectively reduce the impact of human waste on the environment. Although the overall sustainability level of TCSTT technology is grade II, the sustainability performance of TCSTT can further improve by adding supporting facilities and adjusting the equipment option. The local government needs to strengthen the training of rural residents to build, use and maintain TCSTTs properly. In addition, TCSTTs is a good option for villages that are planning to build their own sanitation treatment systems. Rural residents can connect the TCSTTs to the sanitation facilities as a pretreatment process.

The field study of the toilet technology in this village revealed that the model results are valid. This implies that the model can obtain reliable assessment results in the sustainability assessment of rural toilets for which there are many uncertainties. Recent studies have been conducted to evaluate the performance of toilets and sanitation from environmental, economic, and technical dimensions. (Gao et al., 2017; Shi et al., 2018; Firmansyah et al., 2021). Although the present studies provide support for this study, the differences are significant. Firmansyah et al. (2021) discussed the performance of water flushing toilets used in small tropical islands in connection with sanitation. In contrast, the subject of this study is rural toilets in developing areas. In these underdeveloped rural areas, toilets require independent treatment of human waste due to the lack of a sanitation network. Therefore, the toilet technology used in rural areas differs significantly from other regions. In addition, the above studies emphasize the economic and environmental performance of the technology. However, the management and maintenance of toilets in underdeveloped rural areas rely more on the rural residents themselves (Wu et al., 2021). This means that the proper operation of toilets depends on the willingness of rural residents to accept the toilets, and their ability to manage and maintain the toilets (Poortvliet et al., 2018; Fu et al., 2022). For toilets used in rural areas, sustainability should include environmental improvement as well as the ability to use and maintain the toilets themselves. Therefore, this study evaluates the sustainability of rural toilets in three aspects: economic, services and management, and environmental. This study can help policymakers to select more feasible toilet technologies and promote sustainable development of toilets in developing rural areas.

4 Conclusion

For developing areas, upgrading toilets in rural areas is a meaningful way to stop the spread of fecal-borne disease, reduce poverty, and protect the environment. While some of the upgraded toilets are difficult to operate properly or even abandoned due to the difficulty of acceptance or maintenance by rural residents. Sustainable rural toilet technology mean that the toilets can reduce the environmental pollution caused by human waste while at the same time the toilets are accepted and used consistently by rural residents. The current researches have paid insufficient attention to the impact of rural residents on the sustainable performance of toilet technology. The study builds sustainability assessment indexes of rural toilet technology in three dimensions: economy, environment, and service and management. A sustainability assessment model based on UMT is developed to provide insights for upgrading toilets in rural areas. The RTTSAM is applied to the toilet technology used in Honghai village to illustrate the feasibility and validity.

The results show that the sustainability performance of TCSTT technology used in Honghai Village is high. While the service and management performance of TCSTT technology is general, which means the TCSTTs need to extend processing time and adjust equipment options in Honghai Village. The results of the study indicate that the impact of rural residents may play a crucial role in achieving sustainable rural toilets. And the sustainability performance of the same toilet technology will vary in different environments and changing needs of the rural residents.

Therefore, some practical implications are provided. The government should provide financial support to encourage rural residents to upgrade their toilets. The government should offer technical support for upgrading toilets and monitoring the quality of rural toilets. The government needs to strengthen the publicity of toilet upgrading and educate rural residents about the use and maintenance of toilets. This study contributes to support the upgrading of rural toilets, improve the health of rural residents, enhance the living environment of rural residents, and guide the local government to seek the sustainable development of rural areas.

Data availability statement

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

Author contributions

Conceptualization: SW, QC; Interpretation of the data: SW, QC, B-JH; Review and Editing: SW, QC, XL; Data curation and Formal

Analysis: SW, QC, B-JH, XL; Finally, all authors read the final version of the manuscript and approved accordingly.

Funding

This work is supported by the Shaanxi Provincial Education Department Key Research Program Project "Study on the Mechanism, Measurement and Evaluation of Ecological Construction of Sanitation and Toilets in Northwest Rural China" (project no. 22JZ039); the Nature Science Foundation of Shaanxi Province "The funnel effect of participation behavior of rural residents' toilet and sanitation enhancement in Shaanxi: a study of behavioral mechanisms and intervention strategies" (project no. 2023-CX-RKX-152); the Social Science Research Special Youth Project of Shaanxi Province "Construction technical sustainability evaluation and development strategy study of rural toilet and sanitation in Shaanxi" (project no. 2023qn0088).

Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1112689/full#supplementary-material

SUPPLEMENTARY SCHEDULE S1
1–9 point scale method.

SUPPLEMENTARY SCHEDULE S2
Random index (R.I.) values.

SUPPLEMENTARY SCHEDULE S3
Consistency check of judgment matrix.

SUPPLEMENTARY SCHEDULE S4
The final score of the sustainability assessment indexes.

SUPPLEMENTARY SCHEDULE S5
Single-index unascertained measure matrix.

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