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Assessment of Economic, Environmental, and Technological Sustainability of Rural Sanitation and Toilet Infrastructure and Decision Support Model for Improvement

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Abstract: Sanitation and toilets are important infrastructure for public health and societal stability. However, the adoption of adequate treatment technologies and techniques is a major challenge for both developing and underdeveloped areas. Answering the question of how to improve sanitation and toilet infrastructure in rural areas, for poverty alleviation, inequality mitigation, and good health and well-being under the Sustainable Development Goals, is more challenging compared with urban areas. Decision support models (DSMs) are important for selecting rural sanitation and toilet technologies. However, previous models have not fully respected local standards, needs, and operational environments, and are mainly limited to technological sustainability performance. To overcome such research gaps, this study developed a rural sanitation and toilet technology decision support model (DSM) assessing economic, environmental, and technological sustainability. Both technology and village weighting methods based on 217 general experts and seven local residents, respectively, were adopted to fully tailor indicator weights to rural contexts. The results showed an economic sustainability weight of 0.205, an environmental sustainability weight of 0.466, and a technological sustainability weight of 0.329. The sanitation and toilet technologies were divided into wastewater treatment technologies and toilet technologies, with the former subdivided into primary, secondary, and tertiary wastewater treatment technologies. This study confirmed that the PSO-GWO algorithm outperformed in accuracy and effectiveness. Accordingly, the PSO-GWO algorithm was adopted to demonstrate the optimization of sanitation and toilet technologies in four villages in plateau, mountain, plain, and basin areas. The study can assist local governments in selecting appropriate rural sanitation and toilet technologies during the planning phase. This can enhance the living standards of rural residents and promote sustainable rural development.

Keywords: decision support model; sanitation and toilet technologies; rural areas; developing areas; assessment indicators; PSO-GWO algorithm

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1. Introduction

Sanitation and toilets are essential infrastructure that play a crucial role in supporting the daily lives of residents and maintaining social functioning [1]. Insufficient sanitation and toilets can threaten public health, damage the environment, and exacerbate social inequities [2]. A survey conducted in indigenous communities in Canada reveals a significant correlation between inadequate access to toilets and an increased incidence of gastrointestinal disease and depression [3]. A survey conducted in Natuk, India, shows that the presence of pathogens such as *E. coli* and the risk of their release into the environment decreases with toilet upgrades [4]. While the importance of sanitation and toilets has been acknowledged, the current state of their development remains a challenge. The United Nations World Water Development Report indicates that 46% of the global population lacks access to basic sanitation [5]. Globally, an average of 80% of wastewater is released into the environment without any treatment [5]. According to the Sustainable Development Goals, the sanitation and toilet situation has significantly challenged health and wellbeing, poverty alleviation, inequality reduction, and sustainable community development of numerous areas.

The situation is most severe in rural areas. In rural India, the toilet coverage is 59.5%, while it is a mere 18.5% in Ghana [6]. Accordingly, governments have tried to improve sanitation and toilets in rural areas. However, due to poor technical decision-making, these sanitation facilities and toilets generally operate with inadequate treatment and have not been widely accepted by the rural residents. Consequently, this has hindered the improvement of sanitation and toilets in rural areas. In 2014, the Government of India initiated the Clean India campaign to upgrade toilets in rural areas. However, only 71.3% of households in rural India have toilets, and 3.5% of rural residents have never used the improved toilets due to their unacceptability [7]. In 2019, the Chinese government allocated 7 billion yuan for a toilet revolution, but a study revealed that only 25% of rural households were satisfied with the improved toilets [8].

Many studies have been carried out to develop decision-making models for selecting proper sanitation and toilet technologies. Attri and Singh [9] used a fuzzy multi-criterion decision-making method (MCDM) to compare sustainable wastewater treatment technologies. In Iran, Fetanat and Tayebi [10] applied an extended MCDM for wastewater treatment technology decision-making. Sucu and van Schaik [11] developed a decision support tool for selecting sewage resource recovery technologies using a weighted multi-objective nonlinear programming model. Vasistha and Ganguly [12] used the TOPSIS method to develop an effluent quality evaluation model for assessing water recycling options in municipal wastewater plants. In Spain, Fuentes and Molinos-Senante [13] employed a new variant of the Weighted Russell Directional Distance Model to evaluate the economic and environmental efficiency of wastewater treatment. Hosney and Tawfik [14] proposed a decision tree tool to support technology selection for wastewater recycling in agriculture. Ullah and Hussain [15] developed a decision support system for selecting wastewater treatment technology based on user requirements. Dewalkar and Shastri [16] proposed Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) to evaluate wastewater treatment systems. Zhu and Zhao [17] used Hierarchical Analysis (AHP) and LCA to assess rural toilets and improve their quality. Garfí and Flores [18] evaluated rural toilets using the LCA method, considering both environmental and economic perspectives. Masoud and Belotti [19] used the AHP method to evaluate wastewater treatment options in Al Azraq, Jordan, from a sustainability perspective. In Jordan, Kanchanapiya and Tantisattayakul [20] employed MCDA to make decisions about water reuse options, taking into account economic, social, health, and environmental aspects.

Most studies have evaluated the sustainability of sanitation and toilet technologies from the perspective of the interaction between the environment and technology. However, the treatment quality and service life of rural sanitation facilities and toilets are influenced by the management and maintenance capabilities of rural technicians and the usage habits of rural residents. The characteristics of rural residents' demand for sanitation facilities have been overlooked in current research. From a more sustainable perspective, toilets must be regarded as an integral component of sanitation to meet more than one requirement and function. In rural regions of many countries, for instance, a substantial portion of residents independently utilize outdoor toilets unconnected to sanitation for waste disposal. Accordingly, rural residents can acquire toilet waste as fertilizer [21]. The dispersed nature of rural settlements leads to demand for small-scale wastewater treatment technologies [22]. Overall, the decision-making process for sanitation and toilet technology in rural areas should consider local standards, residents' needs, and the operational environment of facilities to better meet multiple needs and promote sustainable development. This study developed a rural sanitation and toilet technology decision support model (RSTTDSM) using the Particle Swarm Optimization-Grey Wolf Optimization (PSO-GWO) algorithm to promote environmental, economic, and technological sustainability. The objectives of this paper are: (1) to develop an assessment system which can leverage environmental, economic, and technological sustainability; (2) to accurately determine the weights of assessment indicators tailored to rural contexts; (3) to empirically develop a catalogue of rural sanitation and toilet technologies; (4) to identify the most effective and accurate algorithm for determining proper sanitation and toilet technology combinations; and (5) to demonstrate the applicability of the decision support model in representative plateau, mountain, plain, and basin villages. Overall, this study contributes to the sustainable development of rural sanitation and toilets and can practically improve the quality of life of rural residents and safeguard the ecological environment.

2. Materials and Methods

2.1. Conceptual Framework

This study presents an RSTTDSM to help local governments in rural areas in selecting sustainable rural sanitation and toilet technologies. The model identifies 15 indicators across three dimensions: economic affordability, environmental friendliness, and technological adaptability. To determine the final weights for each indicator, a combination of technology and village weights is utilized. The technology weights focus on the sustainability performance of the technology itself, which reflects its sustainability performance in most villages. The village weights consider the village environment, the needs of rural residents, and local regulatory requirements. It indicates the sustainability performance of the technology for a specific village. By using a Combined Weighting Method, the model ensures the relevance of the selected technology to the specific needs of each village. This study categorized technology into four stages: primary, secondary, and tertiary wastewater treatment, and fecal treatment. Due to the high cost and maintenance difficulty of biological treatment technology, only combinations of physicochemical treatment technologies were considered in tertiary wastewater treatment. Then, a database of technology combinations was created to support the calculation of the RSTTDSM. The technology database features physicochemical, biological, and ecological treatment technologies for wastewater, and it features water-based and waterless fecal treatment technologies. The technologies cataloged in the repository are recommended for use by local governments and relevant regulations [23,24]. Hence, these technologies can effectively treat wastewater and feces, ensuring reliable operation in rural areas. For efficiency purposes, this study uses the PSO-GWO algorithm to develop the RSTTDSM. The study suggests that users with a daily treatment capacity of less than 5 m^3/d have the option to choose whether or not to adopt a tertiary wastewater treatment technology combination for ease of management. The framework of the method is shown in Figure 1.

2.2. Problem Formulation

In the context of the RSTTDSM, functionally-driven decision-making aims to identify the technology combination that achieves the highest score in terms of sustainability performance. Various technologies are commonly employed for the concurrent treatment of domestic wastewater and human excreta.

Because many households in rural areas use outdoor toilets that independently dispose of human waste, this study categorized technologies into wastewater treatment technologies and toilet technologies. The combinations of wastewater treatment technologies are further categorized into primary, secondary, and tertiary wastewater treatment technologies. To ensure the practicality of these technologies in rural areas, the study only included technology combinations for wastewater and fecal treatment that are widely used in rural areas, and these combinations were added to the technology combination database. Due to the high cost and maintenance difficulty of biological treatment technology, only combinations of physicochemical treatment technologies were considered in tertiary wastewater treatment. Processes involved in wastewater and fecal treatment are shown in Figure 2.

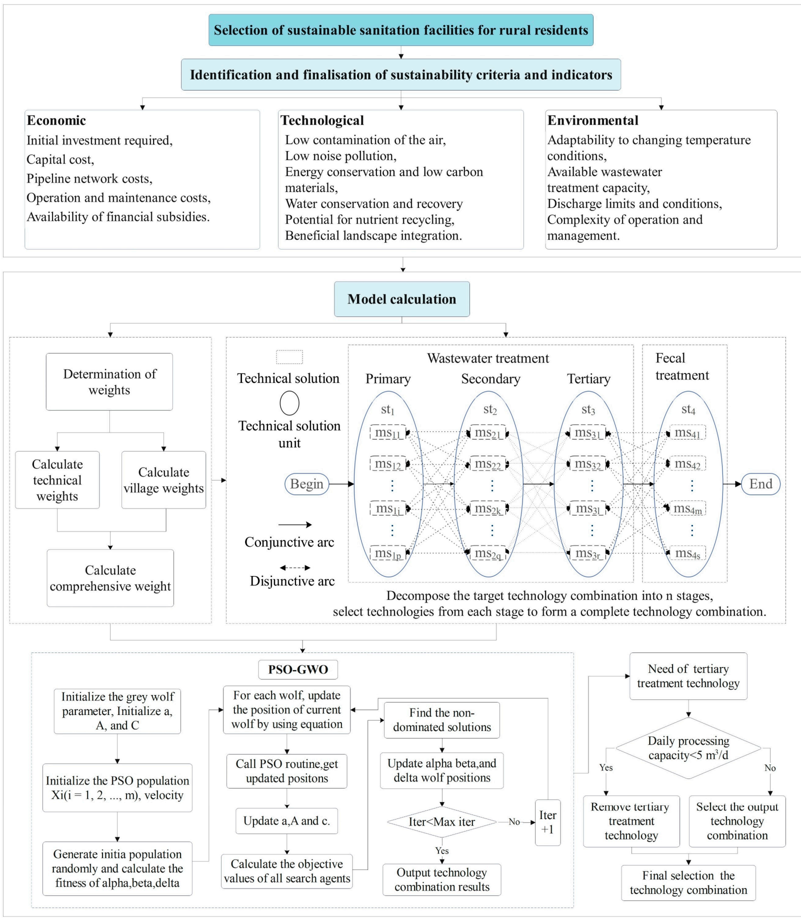


Figure 1. Framework for using the PSO-GWO algorithm to develop the RSTTDSM.

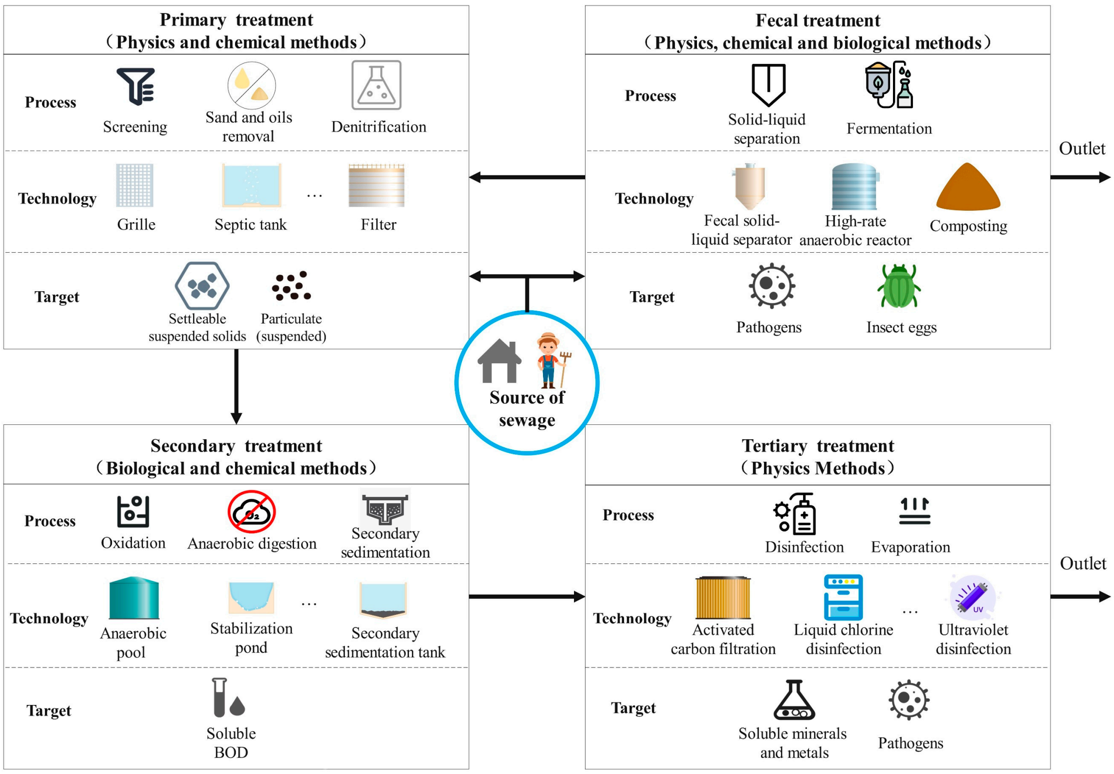


Figure 2. Processes involved in wastewater and fecal treatment.

2.3. Proposed Algorithms

2.3.1. Role of Decision Support Model

The decision-making process for sustainable sanitation and toilet technologies is a multi-objective decision. It is necessary to use a comprehensive approach to support decisions. Boukhari et al. developed a tool using AHP to comprehensively assess the sustainability of water supply and sanitation services from both economic and technological perspectives [25]. Alam et al. used a mixed approach, combining fuzzy comprehensive evaluation (FCE) and AHP, to assess the satisfaction of slum residents with sanitation and toilets [26]. Zhang et al. utilized a combination of AHP and FCE to evaluate the satisfaction of rural residents with rural wastewater treatment technologies [27]. However, AHP has received criticism for its use of an unbalanced scale of judgments and its inability to handle the inherent uncertainty and imprecision in the pairwise comparison process [28]. Yahya et al. employed TOPSIS for decision modeling of wastewater treatment solutions [29]. However, it is difficult for TOPSIS to find schemes that score superior to others on all indicators [30]. Moreover, neither method is suitable for handling a large number of paired comparisons [31,32].

To ensure efficient decision-making processes, Izquierdo utilized a particle swarm algorithm (PSO) to optimize the design of a wastewater collection network [33]. Ye et al. employed a hybrid multi-agent-based PSO for decision-making in urban wastewater treatment network planning [34]. While PSO exhibits fast convergence speed, it can only identify one best particle position at a time, indicating room for further improvement in optimization efficiency [35]. The global search capability of the PSO algorithm is limited. When dealing with heavily constrained problems, it may get trapped in local optima. The PSO-GWO algorithm, on the other hand, employs multi-point convergence to replace the single optimal individual-guided optimization process in the PSO algorithm, thereby enhancing the global search capability in PSO-GWO algorithms [36]. Thus, this study adopted the PSO-GWO algorithm to optimize technology combinations for rural sanitation and toilets. The PSO-GWO algorithm can simultaneously locate multiple particle positions, resulting in rapid convergence and efficient optimization search [37]. Therefore, the PSO-GWO algorithm is suitable to be used for the comparison of different sanitation and toilet technology combinations.

2.3.2. Comparative Analysis

To demonstrate the feasibility of the PSO-GWO method, we compared the results with a GWO method. The algorithm parameters were set as follows: N = 10, d = 88, T_{max} = 500 for the maximum number of iterations, c_1 = 2, and c_2 = 2.

(1) Accuracy analysis. To mitigate the influence of random events on algorithmic results, the robustness of the algorithm is typically strengthened by increasing the number of cycles. In this study, each algorithm was cycled 500 times and made 30 independent decisions during the testing process. Corresponding test results are presented in Table 1.

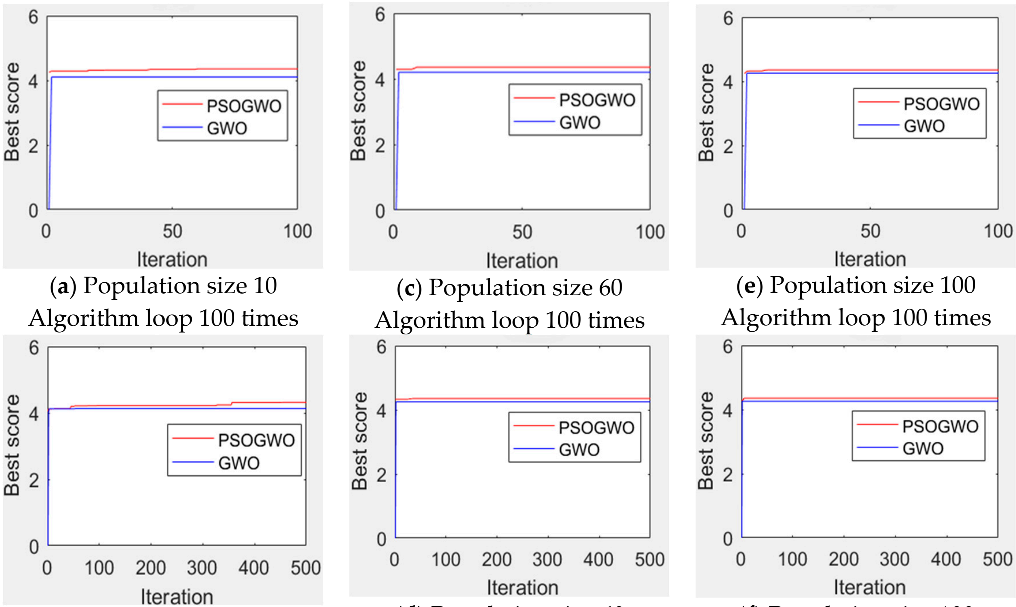
Table 1. Algorithm test results.

Size	**10**		**20**		**40**	
Algorithm	**GWO**	**GWO-PSO**	**GWO**	**GWO-PSO**	**GWO**	**GWO-PSO**
MBF	4.19	4.32	4.23	4.33	4.26	4.34
SD	0.06	0.04	0.03	0.03	0.05	0.02
Runtime	0.86	1.04	1.69	2.03	3.78	4.22

Size	**60**		**100**	
Algorithm	**GWO**	**GWO-PSO**	**GWO**	**GWO-PSO**
MBF	4.28	4.34	4.30	4.35
SD	0.04	0.01	0.03	0.01
Runtime	5.37	6.08	8.93	9.82

Table 1 presents an accuracy analysis of the GWO-PSO algorithm and the GWO algorithm under a limited number of iterations. Mean best fitness (MBF), an indicator that reflects the accuracy of the algorithm, is reported. Additionally, the standard deviation (SD) of the adaptation value is calculated to evaluate algorithmic robustness. The results demonstrate that the GWO-PSO algorithm outperforms the GWO algorithm in both accuracy and robustness while completing the same number of cycles. Moreover, the running time of the GWO-PSO algorithm is comparable to that of the GWO algorithm. Therefore, the GWO-PSO algorithm is a suitable candidate for RSTTDSM.

(2) Convergence analysis. To evaluate the optimization effect and efficiency, we conducted further convergence performance tests on the GWO-PSO algorithm. Various parameters were employed to compare and assess the convergence speed of both the GWO-PSO algorithm and the GWO algorithm, as visualized in Figure 3.



(**a**) Population size 10
Algorithm loop 100 times

(**c**) Population size 60
Algorithm loop 100 times

(**e**) Population size 100
Algorithm loop 100 times

(**b**) Population size 10
Algorithm loop 500 times

(**d**) Population size 60
Algorithm loop 500 times

(**f**) Population size 100
Algorithm loop 500 times

Figure 3. Convergence curve of algorithm.

Figure 3 plots the logarithmic fitness value against the number of cycles. Figure 3a,c,e illustrates the evolution curve of the GWO-PSO and GWO algorithms for a loop iteration count of 100. Similarly, Figure 3b,d,f displays the evolution curves of the GWO-PSO and GWO algorithms for a loop iteration count of 500. The red curve corresponds to the GWO-PSO algorithm, which consistently outperforms the blue curve, representing the GWO algorithm, as shown in Figure 3. This demonstrates the faster convergence and higher optimization efficiency of the GWO-PSO algorithm.

The convergence curves reveal that as the number of iterations increases, the red curve representing the GWO-PSO algorithm exhibits a slight upward trend, while the blue curve representing the GWO algorithm becomes relatively flat. This indicates that the GWO-PSO algorithm continues to explore new advantages with increasing iterations and demonstrates excellent performance in escaping local optima and avoiding stagnation. The slope of the blue curve is greater than that of the red curve, indicating that the efficiency of the GWO-PSO algorithm is higher than that of the PSO algorithm. Consequently, the GWO-PSO algorithm possesses superior optimization capability compared to the GWO algorithm. Moreover, Figure 3 illustrates that as the population size and number of iterations increase, the convergence and optimal times of both the GWO-PSO and GWO algorithms decrease. To ensure the reliability and efficiency of the model's decisions, we set the T_{max} to 500 and the algorithm populations to 100.

2.4. Indicator Identification

The study conducted a literature review to identify indicators across three dimensions: economic affordability, environmental friendliness, and technological adaptability. The economic affordability dimension comprises five indicators, the environmentally friendly dimension includes six indicators, and the technological adaptability dimension encompasses four indicators [38,39].

Economic affordability: Economic affordability means ensuring that the costs associated with the technology's construction, operation, and maintenance are financially feasible for rural residents. Economic affordability indicators consider the overall cost of rural sanitation and toilet construction and the potential for financial subsidies to guarantee the economic viability of the selected technology for rural residents. This dimension comprises indicators of initial investment, capital cost, pipeline network cost, operation and maintenance cost, and availability of financial subsidies. The initial investment refers to expenses incurred to facilitate the commencement of the construction project before its actual construction [40]. Construction costs encompass overall expenses accrued in the project's construction, comprising both building and equipment procurement expenses [41]. Pipeline network costs include expenses associated with constructing a drainage network that connects wastewater treatment facilities to rural residential pipes [42]. The requirements for constructing a drainage network vary across villages, contingent upon factors such as population density and ground slope. Therefore, the study lists pipeline network costs and construction costs separately. Operation and maintenance costs refer to expenses necessary to ensure the effective functioning of facilities, including activities like facility management and maintenance [40,41,43]. Financial subsidies serve as economic support to promote the improvement of rural sanitation and toilets [42,44].

Environmentally-friendly: Environmental friendliness focuses on the environmental impact of sanitation and toilet technologies, as well as their capacity to recycle resources. Environmentally-friendly indicators consider the potential positive and negative impacts on the environment that may arise during the operation of sanitation and toilet infrastructure, providing a more comprehensive evaluation of the potential environmental effects of the technology. This dimension comprises indicators of low contamination of the air, low noise pollution, energy conservation and low-carbon materials, water conservation and recycling, potential for nutrient recycling, and beneficial landscape integration. Low contamination of the air examines the potential for air pollution generated by sanitation facilities and toilets during their operation [39,40,45]. Low noise pollution investigates the level of noise generated by sanitation facilities and toilets during operation [45]. Water conservation and recycling focuses on water consumption during the treatment process and the potential for reusing treated wastewater [40,43,46]. Energy conservation and low-carbon materials refer to the energy requirements and proportion of low-carbon materials used in sanitation facilities and toilets [42]. Potential for nutrient recycling examines the ability of the technology to recycle N and P from feces, urine, and wastewater [41,42]. Beneficial landscape integration focuses on whether the technology enhances the landscape and environmental conditions in its surroundings [40].

Technological adaptability: Technical adaptability focuses on the technology's adaptability, pollutant treatment capacity, and requirements for management and maintenance. Technological adaptability indicators assess the technology's capacity to adapt to environmental conditions and its maintenance and management requirements, ensuring the sustainable and enduring operation of the selected technology. This dimension comprises indicators of adaptability to changing temperature conditions, available treatment capacity, discharge limits and conditions, and complexity of operation and management. Adaptability to changing temperature conditions refers to the range of operating temperatures within which the technology can function properly, encompassing both minimum and maximum limits [39,40]. Available treatment capacity focuses on the ability of the technology to treat wastewater or feces [41,45]. Discharge limits refer to the regulatory control level for discharge to the environment that can be achieved by the facility's treated output [39,45]. The complexity of operation and management refers to management requirements and operational challenges associated with operating, maintaining, and managing the technology [42,47].

2.5. Weight Distribution

The study employed a combination of technology weights and village weights to determine the index weights. The technology weights reflect the perspectives of professionals and focus on the overall sustainability of the technology in various scenarios, while village weights reflect the perspectives of participants involved in the management, maintenance, and utilization of rural sanitation and toilets and focus on the technology's sustainability at the village level.

2.5.1. Quantification of Technology Weight

The technical weight (w^B) quantifies the correlation between the indicators and the sustainability of the technology. To determine technical weights, we administered a questionnaire survey to professionals employed in the fields of rural sanitation and toilet design, construction, operation, and maintenance, as well as environmental testing and monitoring. The researchers aimed to assess the significance of indicators for the sustainability of rural sanitation and toilet technologies. A 5-point Likert scale, ranging from 1 (indicating "not important") to 5 (indicating "important"), was utilized in the questionnaire (Tables S1 and S2). We received 234 questionnaires, and 17 were excluded due to incompleteness or contradictions. The final response rate was 93%, with 217 valid questionnaires. The demographic characteristics of the respondents are shown in Table 2.

Table 2. Descriptive statistics.

Factor	Options	N (%)	Factor	Options	N (%)
Occupation	Professor	50 (23.04%)	Education level	High school and below	102 (47%)
	Engineering designer	46 (21.2%)		Undergraduate	74 (34.1%)
	Civil Engineer	26 (11.98%)		Master's degree or above	41 (18.9%)
	Environmental Engineer	56 (25.81%)	Years of experience	Less than 6 years	64 (29.49%)
	Environmental monitors	39 (17.97%)		6–12 years	114 (52.53%)
				More than 12 years	39 (17.97%)

This study employed structural equation modeling (SEM) to analyze survey data and normalize path coefficients for obtaining the technical weights. The weight of each indicator is shown in Table 3.

Table 3. Criteria and indicators.

Criteria (CR)	w^B	Indicators (INs)	Reference	w^B
Economic affordability (EA)	0.205	R11 Initial investment	[40]	0.185
		R12 Capital cost	[41]	0.171
		R13 Pipeline network costs	[42]	0.221
		R14 Operation and maintenance costs	[40,41,43]	0.249
		R15 Availability of financial subsidies	[42]	0.174
Environmentally friendly (EF)	0.466	R21 Low contamination of the air	[39,40,45]	0.144
		R22 Low noise pollution	[45]	0.156
		R23 Energy conservation and low carbon materials	[40–42,46]	0.158
		R24 Water conservation and recycling	[40,43,46]	0.191
		R25 Potential for nutrient recycling	[39]	0.182
		R26 Beneficial landscape integration	[40]	0.168
Technological adaptability (TA)	0.329	R31 Adaptability to changing temperature conditions	[39,40]	0.165
		R32 Available treatment capacity	[41,45]	0.221
		R33 Discharge limits	[39,45]	0.322
		R34 Complexity of operation and management	[45,47]	0.292

2.5.2. Quantification of Village Weight

The utilization of village weight (w^E) ensures the relevance of decision-making outcomes, considering the varied environmental characteristics and usage requirements observed in different villages. The quantitative criteria for w^E based on relevant research and standards are shown in Appendix A [48–50]. Scoring should involve the participation of a minimum of five local stakeholders, including village residents, professionals from sanitation and toilet design, construction, and management industries, as well as environmental inspectors. Each participant will evaluate the items based on quantitative criteria tailored to the village context.

$$e_i = \frac{a_i}{b_i} \quad (1)$$

$$w^E = [e_1, e_2, \ldots, e_m] \quad (2)$$

where e_i is the w^E of a single indicator; m is the number of indicators; a_i is the item score obtained according to the w^E quantitative standard; b_i is the total score of each item based on the w^E quantitative standard. w^E is obtained by normalizing e_i.

2.5.3. Quantification of Final Weight

Due to the limitations of the traditional weight determination method, this paper utilizes a combination of technology weights and village weights to determine indicator weights. Technology weight focuses on the sustainable performance of the technology in typical scenarios. Village weight focuses on the sustainable performance of the technology in specific villages. The combined weight (w^F) is determined by the following equation [51]:

$$w^F = Z_B w^B + Z_E w^E \quad (3)$$

where w^B is technology weights, w^E is village weights, Z_B is the technology weight combination coefficient, and Z_E is the village weight combination coefficient. In a typical village, the combination coefficients are $Z_B = 0.5$ and $Z_E = 0.5$. The combination coefficients of $Z_B = 0.2$ and $Z_E = 0.8$ are assigned when a village exhibits specific requirements for onsite sanitation and toilet improvements. This encompasses scenarios where a village experiences an annual amplitude of temperature greater than 32 °C, is situated at an altitude exceeding 2000 m above sea level, or is around a nature reserve, water source protection area, or other location with specific emission standards.

3. Study Area

Western China comprises 12 provinces, cities, and autonomous regions. At present, the harsh climate has caused the economic development of the western region, particularly in rural areas, to fall behind that of other regions [52]. In 2021, the annual per capita disposable income in western rural areas was 2426.95 USD [53]. Poor economic conditions have led to a lag in the development of rural sanitation and toilets compared to other regions. Currently, 70.25% of rural toilets in western China are hygienic, while only 40.67% can safely treat human waste [54]. Furthermore, the development of sanitation is even further behind, with only a 12.42% domestic wastewater treatment rate in rural western China [55,56]. This untreated wastewater poses significant health and ecological risks to rural residents. Therefore, it is imperative to select sustainable sanitation and toilet technologies to promote the safe treatment of human waste and wastewater, protect the ecological environment, and drive sustainable development in the region.

This study developed the RSTTDSM to assist rural residents in selecting sustainable sanitation and toilet technologies (Table S3). To validate the model, one rural village was selected as a case study from each of the following regions: plateau, mountain, plain, and basin (Table 4). The first case was in Shunjiang 2 village, situated in the plateau region of Sichuan Province at an altitude of 2850 m. The village experiences an arid climate, characterized by an annual temperature amplitude of 20 °C. The tourism service industry serves as the primary economic source for the residents of Shunjiang 2 village. The volume of wastewater generation varies according to the tourist influx. While most of the village is connected to a drainage network, it lacks wastewater treatment facilities. The second case study was in Ren village, situated in a mountainous region of Shaanxi Province. The primary economic resources of the population rely on agriculture, where the common practice involves the utilization of fecal waste as a fertilizer. However, it is important to note that Ren village lacks a unified drainage line and does not have any wastewater treatment facilities in place. Additionally, the majority of residents still use dry latrines.

Table 4. General characteristics of the four case study areas.

General Characteristics	Case Study 1	Case Study 2	Case Study 3	Case Study 4
Region	Plateau (Shunjiang 2 village)	Mountainous (Ren village)	Plain (Chaganchaidamu village)	Basin (Zhongba village)
Climate	Wet and rainy, low winter temperatures	Cold winters, hot and rainy summer	Drought and low precipitation	Moist and rainy
Elevation within the area (m)	0 900 1800 2700	0 900 1800 2700	0 900 1800 2700	0 700 1800 2700
Average annual precipitation (mm)	0 300 600 900 1200	0 300 600 900 1200	0 300 600 900 1200	0 300 600 900 1200
Population	1500	3783	916	1123
Income sources	Tourism	Agriculture	Agriculture, livestock, tourism	Agriculture
Centralized drainage facilities				
Wastewater treatment facilities				
Status of drainage facilities				
Pit latrines				
Status of toilets				

The third case study examined Chaganchaidamu village in the plains region, specifically in Inner Mongolia, China. It is characterized by a semi-arid climate with an annual temperature amplitude of 33 °C. The economy of the village relies on agriculture, livestock, and tourism. The common practice of using fecal waste as fertilizer supports agricultural activities. While the village has a centralized drainage network, it lacks proper wastewater treatment facilities. Half of the residents use dry latrines, while the other half use flush latrines. The fourth case study examined Zhongba village, which is located in the basin region. Zhongba village is located in Shaanxi Province, China. The climate of Zhongba village is characterized by high humidity and frequent rainfall. Agriculture serves as the primary source of income, and the practice of using fecal waste as fertilizer is widespread. Zhongba village lacks a unified drainage system and does not have any wastewater treatment facilities. The majority of rural residents use water latrines, while those residing near the foothills still rely on dry latrines. The four villages exhibit variations in topography, climate, and the current state of sanitation and toilets. Disparities exist in the villagers' requirements and the practical operational environment of the sanitation and toilet facilities. Hence, the selected villages are ideal for evaluating the reliability of the RSTTDSM.

4. Results and Discussion

A total of seven individuals were invited to participate in the ranking of the w^E. The participants included one village official and one villager from a case study village, as well as a drainage designer, a drainage engineer, a wastewater plant manager, a local wastewater facility maintenance person, and an environmental inspector (Table S5). The participating experts have long been engaged in work related to rural sanitation and toilets, possessing a comprehensive understanding of such facilities in rural areas. The participating villagers and village officials serve as representatives of the local community's requirements. The weight distribution results are shown in Table 5.

Table 5. Details of the weight distribution.

CR	Ins		Case Study 1		Case Study 2		Case Study 3		Case Study 4	
			Z_E **0.8**	Z_B **0.2**	Z_E **0.5**	Z_B **0.5**	Z_E **0.8**	Z_B **0.2**	Z_E **0.5**	Z_B **0.5**
		w^B	w^E	w^F	w^E	w^F	w^E	w^F	w^E	w^F
EA	R11	0.185	0.112	0.127	0.255	0.220	0.202	0.199	0.284	0.235
	R12	0.171	0.179	0.177	0.174	0.173	0.253	0.237	0.277	0.224
	R13	0.221	0.157	0.170	0.133	0.177	0.242	0.238	0.124	0.173
	R14	0.249	0.291	0.283	0.13	0.190	0.118	0.144	0.127	0.188
	R15	0.174	0.261	0.244	0.308	0.241	0.185	0.183	0.187	0.181
EF	R21	0.144	0.223	0.207	0.202	0.173	0.143	0.143	0.140	0.142
	R22	0.156	0.204	0.194	0.135	0.146	0.102	0.113	0.218	0.187
	R23	0.158	0.111	0.120	0.226	0.192	0.096	0.108	0.286	0.222
	R24	0.191	0.107	0.124	0.129	0.160	0.326	0.299	0.068	0.130
	R25	0.182	0.073	0.095	0.168	0.175	0.257	0.242	0.25	0.216
	R26	0.168	0.282	0.259	0.136	0.152	0.076	0.094	0.115	0.142
TA	R31	0.165	0.185	0.181	0.420	0.293	0.315	0.285	0.124	0.145
	R32	0.221	0.214	0.215	0.147	0.184	0.216	0.217	0.410	0.316
	R33	0.322	0.459	0.432	0.31	0.316	0.136	0.173	0.189	0.256
	R34	0.292	0.165	0.190	0.124	0.208	0.333	0.325	0.277	0.285

Note: The coefficients Z_B and Z_E were assigned values of 0.2 and 0.8, respectively, for the Shunjiang 2 villages, which are located at an altitude higher than 2000 m.

Table 6 shows the outcomes of the modeling decisions.

Table 6. The results of the RSTTDSM.

	Wastewater Treatment Technology			Toilet Technology
	Primary	Secondary	Tertiary	
Case study 1	Grating + Regulating tank + Sedimentation tank	Contact oxidation + Sedimentation tank + Constructed wetland	Activated carbon filtration + Chlorine-containing disinfectant tablets	Flush toilets (connected to sewerage)
Case study 2	Grating + Sedimentation tank	Anaerobic filter+ Constructed wetland	Activated carbon filtration + Chlorine-containing disinfectant tablets	Three-compartment septic tank toilet
Case study 3	Grating + Septic tank	Constructed wetland + Oxidation pond	Activated carbon filtration + Chlorine-containing disinfectant tablets	Double pit alternating toilet
Case study 4	Grating + Sedimentation tank	Integrated purification tank	Activated carbon filtration + Chlorine-containing disinfectant tablets	Three-compartment septic tank toilet

4.1. Case Study 1—Shunjiang 2 Village

The modeling results suggest that the optimal primary wastewater treatment technology for Shunjiang 2 village is a combination of grating, regulating tanks, and sedimentation tanks. Grating can help mitigate the issue of high impurity levels in sewage caused by open sewerage systems in villages. Regulating tanks are highly effective at reducing suspended solids, mitigating fluctuations in treatment load, and homogenizing water quality. Additionally, sedimentation tanks provide a further reduction in suspended solids in wastewater. Due to consistently low temperatures in the alpine mountainous area of Shunjiang 2 village, it is crucial to ensure the capacity of the facility even in cold conditions. Therefore, the model recommends utilizing a combination of contact oxidation, sedimentation tanks, and constructed wetland technology as the secondary wastewater treatment approach. This combination is recommended due to its effectiveness in maintaining treatment efficiency even in cold conditions. The RSTTDSM suggests employing a combination of activated carbon filtration and chlorine-containing disinfectant tablets as tertiary wastewater treatment technologies. Activated carbon adsorption is highly effective at removing pollutants that are resistant to microbial degradation, thereby reducing the biochemical oxygen demand (BOD) of the wastewater. Additionally, activated carbon adsorption is less susceptible to the influence of water temperature and necessitates minimal maintenance. Conversely, chlorine disinfection tablets offer simplicity in usage and ease of storage.

The model recommends utilizing flush toilets directly connected to the wastewater treatment facility for excreta disposal. This result is due to the full coverage of the drainage network in Shunjiang 2 village, eliminating the necessity for fecal utilization. The user-friendly nature of flush toilets, coupled with their capability to effectively treat waste when linked to a wastewater treatment facility, rendered them well-suited for adoption in Shunjiang 2 village.

4.2. Case Study 2—Ren Village

In the case of Ren village, the RSTTDSM selected grating and sedimentation tanks as the primary treatment technology. This combination demonstrates efficacy in the treatment of suspended solids in wastewater while mitigating the impacts of varying wastewater volumes. As for the secondary treatment technology, the RSTTDSM chose anaerobic filters and constructed wetlands. Anaerobic filters exhibit resilience against shock loads, eliminate the need for sludge return, and boast simplified operation and management. Additionally, artificial wetlands can remove nitrogen, phosphorus, and suspended solids while enhancing the aesthetic appeal of the environment. This technology combination offers efficient sewage treatment at a cost-effective rate, making it highly suitable for implementation in Ren village. RSTTDSM implemented activated carbon filtration and chlorine-containing disinfectant tablets as the chosen tertiary wastewater treatment technologies. These methods offer user-friendly operation and consistent treatment outcomes.

RSTTDSM suggested the implementation of three-compartment septic tank toilets as an efficient method for human waste treatment. This type of toilet utilizes anaerobic fermentation to treat human waste, making it especially suited for Ren villages with mild climates. And effluent produced by these toilets undergoes thorough fermentation and can be directly utilized as fertilizer, showcasing an effective approach to nutrient recycling.

4.3. Case Study 3—Chaganchaidamu Village

The RSTTDSM proposes the utilization of grating and septic tanks to treat the debris and suspended solids present in the wastewater in Chaganchaidamu village. This combination guarantees the quality of the effluent and enhances the effectiveness of subsequent secondary effluent treatment. Grating and septic tanks are well-suited for the cold climate prevalent in Chaganchaidamu village, as their treatment capacities are relatively unaffected by low temperatures. For secondary wastewater treatment, the RSTTDSM selected constructed wetlands and oxidation ponds due to their low cost, energy efficiency, and environmental friendliness. Both technologies are reliable in cold areas. To ensure convenience and cost-effectiveness, the RSTTDSM chose activated carbon filtration and chlorine-containing disinfectant tablets as the tertiary wastewater treatment technology.

The system utilizes double pit alternating toilets as the toilet technology, given that a majority of residents use outdoor toilets in this village. This technology is capable of withstanding low temperatures, is easy to manage, and ensures dependable fecal disposal.

4.4. Case Study 4—Zhongba Village

In the mild climate of Zhongba village, the RSTTDSM proposes a combination of primary treatment technologies: grating and sedimentation tanks. This combination can effectively treat suspended solids in the effluent, alleviating the burden on secondary wastewater treatment facilities. For the secondary treatment technology combination, the RSTTDSM suggests utilizing integrated purification tanks, which are decentralized and small-scale wastewater treatment equipment. This solution is well-suited for the scattered settlements in Zhongba village, where the challenging terrain makes it impractical to construct a centralized sewage network. The RSTTDSM recommends the use of three-compartment septic tank toilets for fecal disposal in Zhongba village due to the high temperatures and the need for fecal use. The toilet is easy to use and effective in treating fecal matter, making it suitable for the village's mild climate.

The case study results demonstrate that the selected combination of technologies for the RSTTDSM can be adapted to the local environment and provide reliable treatment effects, proving the reliability of the RSTTDSM. This suggests that the RSTTDSM can assist local governments in rural areas in making decisions regarding rural sanitation and toilet technologies.

5. Conclusions

Inadequate access to sanitation and toilet infrastructure threatens the environment and public health in China's rural areas. The challenge of selecting appropriate technology presents a significant obstacle for local governments in improving toilets and sanitation in rural areas. Thus, the study constructed a decision-making model for selecting sustainable rural sanitation and toilet technologies. Fifteen indicators were chosen to construct an indicator system based on the three dimensions of economy, technology, and environment. A combination weight method was used to ensure the appropriateness of the decision-making results. The PSO-GWO algorithm was used to develop the RSTTDSM to reduce computational time. The RSTTDSM was validated through case studies. The model can assist local governments in selecting sustainable sanitation and toilet technologies during the planning stage. This assistance contributes to both an improvement in living standards for rural residents and the sustainable development of rural areas. The model can be further modified to broaden its applicability based on site requirements, regulatory considerations, and technological advancements. Thus, the model serves as a reliable baseline for research in this field, contributes to the universalization of sanitation in rural areas, and enhances the well-being of rural residents.

However, the study has some limitations. The indicator system established by the model is primarily designed for temperate continental climate regions. When applying the model in other climatic regions, adjustments to the model indicators are necessary to align with the preferences of the local residents. New technologies should be incorporated into the technology database to align with the modernization of sanitation and toilet technologies. Further studies could explore the implementation of innovative algorithms to enhance the optimization efficiency of the model.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16114384/s1, Table S1: Quantitative economic performance standards for village weights; Table S2: Quantitative standards for technological weights; Table S3: Rural sanitation and toilet technology combination; Table S4: Rural sanitation and toilet technology combination. Table S5 Descriptive statistics of participants. References [40–43,45–47,57–67] are cited in the supplementary materials.

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Appendix A

The objective of functional decision-making via the RSTTDSM is to select the optimal combination of units and integrate them into a comprehensive technical solution. Ultimately, the final technological combination selected in the RSTTDSM is a combination of multi-stage technologies. According to the degree of wastewater treatment, wastewater treatment technology can be categorized into primary wastewater treatment technology combinations, secondary wastewater treatment technology combinations, and tertiary wastewater treatment technology combinations. Since toilets in rural areas are independent of sanitation, the toilet technology combinations include toilets that are capable of treating excreta independently and those that need to be connected to wastewater treatment facilities. Based on an analysis of the technical characteristics of rural sanitation and toilets, the following assumptions are made:

The different treatment stages are interconnected in a series to create the final technological combination. Within each stage, various combinations of technologies are selected to ensure that they meet the necessary performance requirements for decision-making purposes. In a given treatment stage, only a single technology combination can be chosen. The performance of various dimensions within a technology combination can be independently measured. Through the process of assigning appropriate weights, it is possible to synthesize a comprehensive measure of the performance objectives for a given technological combination. The functional goal decision of the model can be formulated as follows:

The target technology combination, ST, can be decomposed into a series of n-stage technology combinations, $\mathrm{s_{ti}}(i \in \{1, 2, \ldots, n\})$, which can then be combined to form the final technology combination, STL. For each stage of the technology combination $\mathrm{s_{ti}}$, there exist m alternative technology combinations, denoted as $\mathrm{m_{sk}}(k \in \{1, 2, \ldots, m\})$. Therefore, the final technology combination, STL, consists of $\prod_{i=1}^{n}\left(C_{n,m}^{1}\right)$ available options.

Basically, the combination achievement consists of five steps:

(1) Generalization model:

Definition A1. *The digraph* G = (MS, R*) consists of the sets* MS *and* R*. Set* $MS = U_{i=1}^{n} MS_i$ *represents all the technology combinations that can be selected from the n-stage technology combinations in the model. The set* $R = \{r_1, r_2, \ldots, r_h\}$ *represents the conjunctive arc of each technology combination in the neighboring stage. Provide that* $\mathrm{r_{ij,pq}} = (\mathrm{ms_{ij}}, \mathrm{ms_{pq}}) \in \mathrm{R}$*, representing the jth technology combination in the i-stage technology combination, only if* $\mathrm{ms_{ij}}, \mathrm{ms_{pq}} \in \mathrm{MS}$ *and* p-i = 1*. The directed conjunctive arc formed by* $\mathrm{ms_{ij}}$ *and the qth technology combination represents the p-stage technology combination;* $\mathrm{ms_{ij}}$ *is the upper node of* $\mathrm{ms_{pq}}$ *and* $\mathrm{ms_{pq}}$ *is the lower node of* ms_{ij}*.*

Definition A2. *If $MS' \subseteq MS$ and $MS' = \left\{ ms'_j \middle| \left(ms'_j, ms_j \right) \in R \right\}$, it is called the upper node set of ms_{ij}, denoted* $P(ms_{ij})$*, and the technology combination of this upper node set is represented by* (ms_{ij})*. If $MS' \subseteq MS$ and $MS' = \left\{ ms'_j \middle| \left(ms'_j, ms_j \right) \in R \right\}$, it is called the lower node set of* ms_{ij}*, denoted* $N(ms_{ij})$*, and the technology combination of this lower node set is represented by $\overline{N}(ms_{ij})$.*

Definition A3. *For $\forall m_{ij} \in MS$, there is a configuration choice variable allocate $(ms_{ij} = \{0,1\})$, where allocate* $(ms_{ij}) = 0$ *indicates that ms_{ij} does not participate in technology combination formation. Allocate* $(ms_{ij}) = 1$ *indicates that ms_{ij} participates in technology combination formation. Prior to the implementation of the technology combination, $\forall m_{ij} \in MS$, $i \in [1, n]$, $j \in [1, m_i]$, allocate* $(ms_{ij}) = 0$.

The decision-making process for functional goals involves:

In each stage of technology combination, st_i, there are ms_i technology combinations. Starting from the previous-stage technology combination, st_1, one technology combination is sequentially selected from each subsequent-stage technology combination, st_i, following the direction of the conjunctive arc, to form the final technology combination. The ultimate objective of the modeling decision is to choose the optimal combination of technologies from each stage in order to form the final technology combination E*.

$$E^* = \left\{ \overline{P}(ms_{ij}), ms_{ij}, \overline{N}(ms_{ij}) \right\} \tag{A1}$$

(2) Objective function of economic affordability:

The functional objective of economic affordability is to identify the technology combination with the highest economic affordability score. Given that technology combinations are interconnected in series, the economic affordability score is determined by summing the economic affordability scores of the technology combinations at each stage. The functional objective function for economic affordability is as follows:

$$C = \sum_{j=1}^{k_i} H_{ij} C_{ij} \tag{A2}$$

When the technology combination ms_j is selected at the ith stage, $H_{ij} = 1$. Otherwise, $H_{ij} = 0$. C_{ij} represents the economic affordability score of the jth technology combination in the ith stage of the model; k_i represents the number of processing stages.

(3) Objective function of environmental friendliness:

The final score of environmental friendliness is determined by summing the environmentally friendly scores of the technology combinations at each stage. The functional objective function for environmental friendliness is as follows:

$$G = \sum_{j=1}^{k_i} H_{ij} G_{ij} \tag{A3}$$

When the technology combination ms_j is selected at the ith stage, $H_{ij} = 1$. Otherwise, $H_{ij} = 0$. G_{ij} represents the environmentally friendly score of the jth technology combination in the ith stage of the model; k_i represents the number of processing stages.

(4) Objective function of technological adaptability:

The objective of the RSTTDSM decision is to identify the final technology combination with the highest technological adaptability score. This score is calculated by summing up the technological adaptability scores of the combinations across all stages. The functional objective function for technological adaptability is as follows:

$$J = \sum_{j=1}^{k_i} H_{ij} J_{ij} \tag{A4}$$

When the technology combination ms_j is selected at the ith stage, $H_{ij} = 1$. Otherwise, Hij = 0. J_{ij} represents the technological adaptability score of the jth technology combination in the ith stage of the model; k_i represents the number of processing stages.

(5) Integrated functional objective:

Given the challenge of simultaneously optimizing functional objectives in various dimensions, the functional objective decision of RSTTDSM becomes a multi-objective optimization problem that requires determining the overall functional objective by considering functional objective weights. The formula for calculating the model's integrated functional objective is as follows:

$$MaxZ = w_1C + w_2G + w_3J \quad (A5)$$

where w is the weight vector.

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