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Governance of rural solid waste under a multi-subject governance model

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Rural solid waste (RSW) exhibits distinct characteristics compared to municipal solid waste (MSW), such as dispersed distribution, long governance chains, and low recycling value, making it unsuitable to apply the same management measures as MSW. Government-led RSW management results in excessive administrative costs, and the inherent characteristics of RSW reduce market enthusiasm for its management. To address these issues, this paper integrates the " multi-subject governance " model with RSW management and establishes a systematic evaluation index system for RSW governance. Utilizing the Best-Worst Method (BWM), key factors were identified. Utilizing the VIKOR method, representative provinces in China were used as case studies to validate the scientific nature of the evaluation indices. The research findings indicate that the multi-subject governance model is an effective approach for RSW management. Key factors influencing RSW management effectiveness include various governmental measures, waste sorting, and a long-term multi-subject governance mechanism. Case analysis reveals a strong correlation between the level of economic development and the effectiveness of RSW management. However, constructing a government-led, multi-subject collaborative urban-rural interconnected RSW management model can effectively address RSW management issues in economically underdeveloped areas. This research provides innovative solutions for RSW management, contributing to high-quality and sustainable development in rural areas.

Keywords Rural solid waste, Multi-subject governance, The best-worst method, VIKOR

Rural solid waste (RSW) represents a significant source of environmental pollution in rural areas. Its effective management is crucial for the health of rural residents and the safety of the rural ecological environment. RSW is characterized by several distinctive features: firstly, the rural areas are vast and sparsely populated, leading to non-centralized waste distribution. Secondly, the variety and volume of RSW are increasing annually, thereby enhancing its destructive impact. Thirdly, the recyclable value of RSW is relatively low compared to municipal solid waste (MSW), complicating the establishment of a closed-loop waste supply chain in rural settings[1,2].

These characteristics, coupled with inadequate management infrastructure and low environmental awareness among residents, significantly complicate the governance of RSW. For underdeveloped countries and regions, rural waste has become a substantial threat to environmental safety. For instance, according to 2023 statistics from China, nearly a quarter of RSW has not been appropriately managed, leading to common issues such as disorderly waste dumping, open-air burning, and garbage buildup near villages. These unmanaged wastes not only breed pathogens and spread diseases but also contaminate the soil, groundwater, and surface water.

Countries around the world have adopted different management models for rural solid waste. The United States primarily employs a model where the government supports the contracting out of waste treatment services. Waste collection and transportation are undertaken by multiple small-scale companies, and waste management is entirely market-driven. In terms of waste management facilities, a "government-funded, privately operated" model has been implemented, which has been successful in the US[3]. A survey conducted across over 300 local communities has shown that private contracting saves approximately 25% of costs compared to direct government service provision[4]. Germany, concerned about the uncontrollable commercial activities of private entities, adopts a government-led model while encouraging the participation of social organizations and the public in waste management[5]. Japan applies lean production concepts to rural waste governance, promoting precise recycling and processing to ensure maximum waste recycling. In Japan, rural waste management costs

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are primarily covered by farmers' payments, with the government providing financial support for waste recycling projects[6].

These practices from developed countries, although varying in governance philosophies, share commonalities such as encouraging the participation of multiple subjects in rural waste governance, coordinating relationships between these subjects through incentive mechanisms, and making scientific planning tailored to the rural development realities of each country. However, many underdeveloped countries and regions have yet to find a rural waste governance model suited to their national conditions. Restricted by economic development levels and environmental consciousness, these areas cannot merely replicate the governance models of developed nations but need targeted reforms addressing existing critical problems.

Previous research has predominantly focused on the management of municipal solid waste (MSW). Extensive studies have been conducted on waste categorization, policy implementation, and the construction of recycling supply chains[7–12]. Additionally, there have been specialized studies on medical waste, plastics, discarded electrical appliances, and other special urban wastes[3,13–15]. RSW governance often replicates findings from MSW management, frequently overlooking issues like inconvenient waste transport and incomplete recycling systems in rural areas. The multi-subject governance (MSG) model, an extension of "multi-centric" governance approaches, represents an essential pathway for the modernization of public-interest environmental governance since it helps in addressing insufficient government supervision or capability deficits[16,17]. The MSG model has been predominantly applied to fields like population planning, education, and air pollution, with a lack of systematic research on its application in RSW governance[18–20]. The multiple subjects under the MSG model have differing interest considerations, which may lead to the failure of government regulation and market operation. Existing research has not yet discussed how to identify the barriers in the RSW governance system and thus design effective coordination mechanisms to address them.

This paper constructs an evaluation index system for RSW governance under the MSG model. It determines the weight of influencing factors, identifies bottlenecks, addresses blind spots across the emission-management-supervision process of RSW governance, and designs coordination mechanisms to ensure efficient collaboration among all subjects. Since system performance evaluation and factor weight measurement are typical areas of study within Multi-Criteria Decision Making (MCDM), this paper compares the applicability of various MCDM methods, selecting the Best-Worst Method (BWM) for model construction. The effectiveness of the research findings is verified through case studies on RSW governance in different regions of China. This study explores strategies for RSW governance under the MSG model, contributing to the theoretical and practical enhancement of waste governance systems. Through the application research of the MSG model, the division of responsibilities among multiple subjects within the RSW governance system can be clarified. This model optimizes the environmental governance coordination mechanism, addressing government functional "blind spots." It guides all sectors of society to participate in rural waste management in an orderly and effective manner.

The remainder of this paper is structured as follows: Section two provides a literature review, which summarizes the research findings on rural waste management and MSG, and presents the initial indicator framework for evaluating rural waste management. Section three introduces the research methodology. Section four identifies the key factors in RSW governance. Section five designs a coordination mechanism based on the computational results, and compares the results with previous research. Section six presents the research conclusions and outlines future research directions[14].

Literature review

Current situation and cause analysis of RSW problems

With the rapid development of rural society and the increasing living standard of rural residents, lifestyle changes have led to a continuous increase in both the quantity and variety of domestic waste[21]. The methods of handling domestic waste by rural residents mainly include recycling, landfilling, open-air burning, and dumping in open areas[22]. It found that about 78% of rural populations resorting to open dumping for solid waste disposal[23]. Li et al. noted that reckless dumping of solid waste has polluted approximately 100,000 square kilometers of China's agricultural land[24]. Zeng et al. found that the environmental pollution caused by RSW is characterized by dispersed distribution, wide-ranging pollution sources, and high governance costs, which pose great challenges to the governance of RSW[25].

Some scholars have analyzed the reasons for the RSW problems. Yu et al. suggested that inadequate funding, lack of appropriate technology or effective operational assurance mechanisms are prominent problems in RSW management[26]. Xu et al. posited that insufficient government legislation and inadequate supervision affect the effectiveness of RSW governance[27]. Wang et al. emphasized that the convenience of waste collection facilities significantly influences the behavior of rural residents[22]. Li et al. contended that insufficient environmental awareness and lack of participation in waste management among rural residents is another major factor contributing to the RSW problem[28].

Due to constraints of economic and social conditions in rural areas, RSW treatment has long been a vexing issue. With the increasing emphasis on environmental governance, progress has been made in recent years in rural waste treatment and recycling[29,30], but challenges and issues persist.

The importance of the subjects' action in RSW governance model

RSW governance involves multiple subjects, each playing distinct roles. As more people become aware of environmental issues, the models for RSW governance are continually being updated and improved. Previously, most scholars tended to study the RSW governance model from a single perspective, such as only considering the government[31] or rural residents[28]. These RSW governance models can solve some of problems, but cannot comprehensively address all problems. Some scholars have gradually realized the importance of different subjects in the RSW governance process, and comprehensive consideration is needed in the design of RSW governance

models. Li et al. found that a multi-subject governance model can significantly enhance the efficiency of rural residents' participation in domestic waste management[32]. Scholars have primarily categorized the subjects into three groups: the government, rural residents, and other social organizations (Kuang and Lin 2021; Wei and Jin 2020; Yin, et al. 2024).

The government plays a pivotal and driving role in RSW governance. Cao noted that the government, as the primary operator of RSW management, provides institutional safeguards through policies, legal provisions, and administrative regulations[33]. Agya et al. suggested that RSW management requires government investment in infrastructure, which is currently insufficient and should be strengthened[34]. Wang et al. found that village officials play a crucial role in RSW governance with their organizational and mobilization capabilities[35].

Beyond the government's leading role, rural residents, as the primary contributors to both agricultural and domestic activities, are also major producers of solid waste. Their attitudes and behaviors are crucial in the practical management of rural waste. Liu et al. found that most rural residents do not use the solid waste control measures recommended by the government[36]. Xu et al. observed that most rural residents have a poor environmental consciousness and still hold the belief that environmental sanitation is the government's responsibility[27].

Other social organizations participate in rural waste management through technological innovations and the provision of equipment, thereby playing a significant role by offering technical support and material assistance. Gabriel et al. emphasized the importance of environmental organizations in RSW governance[37]. Shadbahr et al. highlighted that research institutions can aid RSW governance by developing technologies[38]. Yin et al. found that introducing social capital into RSW governance can address the government's fiscal constraints[39]. As rural environmental governance practices continue to progress, the unilateral governance model can no longer meet the needs of the new era. Some scholars believed that corporates' involvement in waste governance can enhance efficiency. Park et al. integrated the governmental mechanism and the market mechanism by introducing an agency system to reform the existing public service provision model. They suggest that RSW governance could adopt a market-led model where the outcome depends on the interplay between government and business[40]. Sun et al. believed that by adopting the Public-Private Partnership (PPP) model, achieving efficient resource recovery management of RSW[41]. Wang et al. emphasized that delegating decision-making power to multiple subjects within a common institutional framework can lead to a more efficient, equitable, and sustainable provision of public goods[42].

Although many solutions have been proposed for RSW governance, it still faces many challenges and issues, necessitating a collaborative effort to establish an effective operational framework that supports long-term RSW governance. Although scholars have proposed various multi-subjects' governance models, current research lacks a comprehensive and effective evaluation system to assess governance effectiveness. Therefore, it is crucial to establish a evaluation system for RSW governance systems.

Evaluation of RSW governance systems

The evaluation of RSW governance systems has long been a focus of scholarly attention. Scholars from various disciplinary backgrounds have conducted thorough investigations into different aspects of RSW governance systems, approaching the subject from a range of perspectives. Darban et al. suggested constructing evaluation indicators for the system based on rural residents' attitudes toward RSW governance. These indicators include residents' satisfaction with governmental waste regulation and the effectiveness of organic and solid waste segregation[43]. Aguirre constructed evaluation indicators for RSW governance based on the current management status, focusing on the management of social institutions, the efficiency of legal enforcement, economic support, environmental education, and citizen participation[44]. Sun further refined the evaluation index system for the logistics performance of RSW collection and transportation[45]. Huang performed an audit evaluation of RSW governance from four perspectives: infrastructure construction, diverse participation in domestic waste management, financial investment in waste governance, and government support[46].

Constructing an evaluation system for RSW governance systems from a multi-subject governance perspective helps focus on the weak links and core issues. After summarizing and synthesizing numerous literatures, various evaluation indicators for RSW governance systems involving multi-subject governance are selected and integrated, and categorized into different dimensions based on their meanings. This paper constructs the framework of the initial evaluation indicator system from five dimensions: (i) Institution, (ii) Personnel, (iii) Logistics, (iv) Processing, (v) Support, with specific descriptions of each indicator provided in Table A1(Appendix).

Methodology

The research design received approval from the Ethics Committee of the School of Information and Business Management at Dalian Neusoft University of Information. In strict compliance with the Helsinki Declaration, our study was conducted following all pertinent guidelines and regulations. Informed consent was obtained from all subjects, who were all duly informed about the purpose of the study and assured of the survey's anonymity. The outcomes of this research will be exclusively utilized for scientific purposes, with a firm commitment to maintaining the confidentiality of personal information.

The Delphi method

Considering the advantages and disadvantages of the Delphi method, this paper uses the Delphi method to optimize the Prototype decision-making structure to address the non-systematic issues arising from summarizing indicators solely through literature research.

The procedures of the Delphi method conducted in this study are shown in Fig. 1:

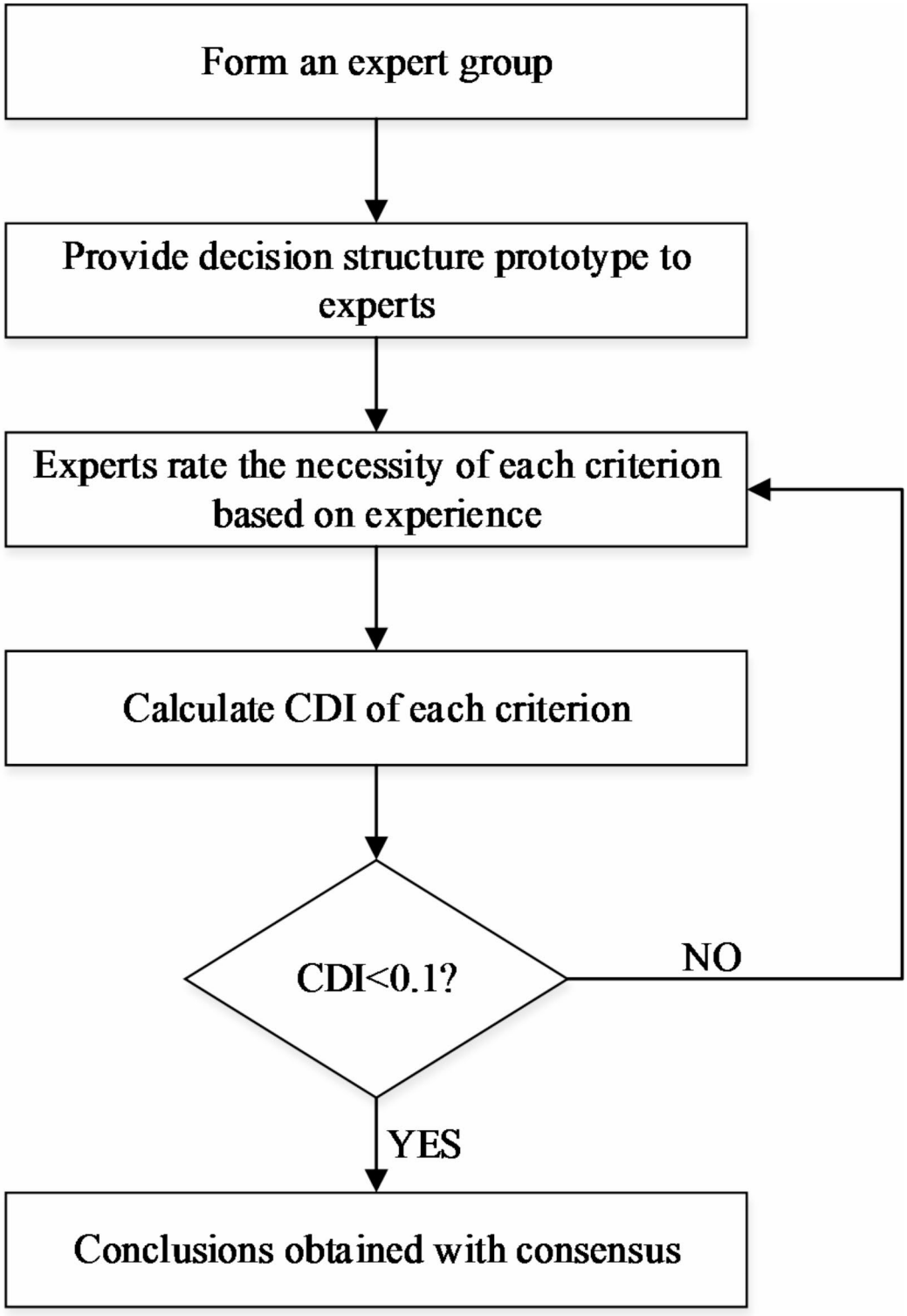

Fig. 1. Procedures of the Delphi method.

Best-worst method (BWM)

BWM is a type of MCDM (Multi-Criteria Decision-Making) method. Compared to other methods, its advantage lies in obtaining consistent results with a small amount of information. The evaluation index system for RSW management under the multi-subject governance model is a theoretical exploration, with some information being difficult to collect or accurately quantify. The application of the BWM method can effectively circumvent this issue.

The implementation steps of the BWM method are as follows:

Step One: Criteria Identification.

Identify a comprehensive list of criteria that are essential to the decision-making process.

Step Two: Best and Worst Criteria Selection.

Select the most critical (best) and the least critical (worst) criteria from the list.

Step Three: Best Criterion Evaluation.

Evaluate the preference of the best criterion over all other criteria using a scale from 1 to 9, creating a Best-to-Others (BO) vector a_{Bj}, where a_{Bj} indicates the preference of the best criterion B over criterion j.

Step Four: Worst Criterion Evaluation.

Assess the preference of all criteria over the worst criterion on a scale from 1 to 9, resulting in an Others-to-Worst (OW) vector a_{jW}, where a_{jW} indicates the preference of criterion j over the worst criterion W.

Step Five: Optimization of Criteria Weights.

The optimal relative weights $(w_1^*, w_2^*, \cdots, w_n^*)$ could be calculated by the min–max model, We transferred the min–max model into the linear programming model (1) as follow:

$$\begin{aligned} &\min \xi^L \\ &s.t. \\ &|w_B - a_{Bj} w_j| \leqslant \xi^L, \ for \ \ all \ \ j \\ &|w_j - a_{jW} w_W| \leqslant \xi^L, \ for \ \ all \ \ j \\ &\sum_j w_j = 1 \\ &w_j \geqslant 0, for \ \ all \ \ j \end{aligned} \tag{1}$$

In this model, ξ^L can be directly considered to be an indicator of the consistency of comparisons. Values of ξ^L close to zero reflect a high level of consistency.

Step Six: Composite Weight Calculation.

Calculate the composite weight $(W_1^*, W_2^*, \cdots, W_n^*)$ for each criterion, integrating its relative weight with its significance within the decision-making context.

$W_i^* = N_j * w_i^* (i = 1, 2, 3 \ldots n; j = 1, 2, 3 \ldots m; n > m)$

Where W_i refers to the composite weight of criterion *i*, N_j refers to the weight of criterion *i* relative to the corresponding aspect *j*, and w_i is its relative weight.

VIKOR

The VIKOR method (Vlsekriterijumska Optimizacija I Kompromisno Resenje) can be viewed as an upgrade of the TOPSIS method. Additionally, in the VIKOR method, decision-makers can determine the importance of each criterion according to their own needs, thus more comprehensively balancing the weights and priorities of different criteria.

The general procedures of the VIKOR method are as follows:

Step One: Determine the group utility value and individual regret value for each evaluation alternative, which can be expressed by the following equations:

$$P_i = \sum_{j=1}^{n} \frac{(w_j \left| U_j^+ - U_j^- \right|)}{(\left| U_j^+ - U_j^- \right|)}, (i = 1, 2, \ldots, m) \tag{2}$$

$$Q_i = \max \left[\frac{(w_j \left| U_j^+ - U_j^- \right|)}{(\left| U_{jJ}^+ - U_j^- \right|)} \right] (i = 1, 2, \ldots, m) \tag{3}$$

U_j^+ and U_j^- represent the positive ideal solution and the negative ideal solution for each attribute, respectively. *Pi* represents the weighted distance of the scheme from the ideal solution, which is used to measure the group utility value of each alternative; *Qi* represents the maximum weighted distance of the alternative from the ideal solution, reflecting the individual regret measure for each alternative.

Step Two: Calculate the compromise measure index value *Ri* for each alternative, using the following formula:

$$R_i = \rho \left[\frac{P^+ - P_i}{P^+ - P^-} \right] + (1 - \rho) \left[\frac{Q^+ - Q_i}{Q^+ - Q^-} \right], (i = 1, 2, \ldots, m) \tag{4}$$

$$\text{where } P^+ = \min_i P_i, \ P^- = \max_i P_i, \ Q^+ = \min_i Q_i, \ Q^- = \max_i Q_i$$

ρ ($\rho \in [0,1]$) is the compromise ranking coefficient representing the weight of group utility, while $1-\rho$ is the weight of individual regret. In this paper, ρ is set to 0.5, it means the decision is made through negotiations and based on a consensus that group utility and individual regret are equally important.

Step Three: Rank the alternatives in descending order based on the obtained values of *Pi*, *Qi*, and *Ri*. This means that the lower the *Ri* value, the better the performance of the alternative.

Step Four: Determine the compromise solution and the constraints that need to be satisfied. If the following two constraints are met, the alternative $A_i^{(1)}$ with the smallest *Ri* value and the best rank is recommended as the compromise solution and the optimal alternative among all alternatives.

Constraint 1: Test for acceptable advantage. The difference between $A_i^{(1)}$) and $A_i^{(2)}$ can be accepted by the decision-maker if it meets the constraint $R_i^{(2)} - R_i^{(1)} >$ DR, where DR = 1/(m − 1), and $R_i^{(2)}$ corresponds to the value of $A_i^{(2)}$in the second-best alternative.

Constraint 2: Test for acceptable stability in multi-attribute group decision-making. Having passed the test for Constraint 1, a further test will be conducted, focusing on the acceptable stability of the best-ranked alternative $A_i^{(1)}$, which means that $A_i^{(1)}$ with the optimal $\mathrm{R_i}$ value ranking must also rank first in the or/and value rankings. If both Conditions 1 and 2 are satisfied, the obtained compromise solution is considered stable in the decision-making process.

If any of the aforementioned conditions are not met, further rules must be applied to obtain a compromise solution, including:

If Condition 1 is satisfied but Condition 2 is not, both $A_i^{(1)}\ and\ A_i^{(2)}$ are considered compromise solutions.

If Condition 2 is satisfied but Condition 1 is not, the compromise solution is determined by the maximum value of $A_i^{(M)}$, satisfying $R_i^{(M)} - R_i^{(1)} <$1/(m-1).

Empirical study

The formal decision structure

Recent research has begun to extend from urban sustainable development to rural sustainable development. China has undergone urbanization and population concentration over the past 30 years. Rural exodus and the aging of the rural population have led to insufficient supervision of RSW. Coupled with high costs and difficulties in waste treatment, RSW has become one of the major problems affecting the ecological environment in China's rural areas. Using China as a case study has representative significance for the global study of RSW management.

Section 2 of this paper confirms the prototype decision-making structure of RSW management under the multi-subject governance model through a literature review. Considering the differences in the years of the literature and the research perspectives of various scholars, we used five experts with rich experience as well as strong theoretical backgrounds in waste management, reverse logistics, and rural economy for this case study, as is shown in Table 1.

Step One: We distributed the prototype decision-making structure to the experts and gathered their feedback through survey questionnaires and face-to-face discussions.

Step Two: The experts were asked to score each index on a scale from 0 to 10, with higher scores indicating a greater necessity for the index. In Table A2(Appendix), we calculated the mean, variance, and CDI value for each index based on the experts' scores. The results show that the CDI values of some indices exceed 0.1, indicating that the experts did not reach a consensus on the selection of these indices.

Step Three: The expert group provided explanations for the scores of the indices with significant discrepancies and re-scored these indices. After multiple rounds of repetition, the CDI values for each criterion were all below 0.1, indicating that the expert group had reached a consensus on all the indices. Meanwhile, upon deliberation by the expert group, it was suggested that indices with a mean score below 6 be eliminated. The formal decision-making structure is shown in Table 2.

Identifying key factors

In this paper, we follow the BMW process to calculate the absolute weight of each index. and described the workflow of experts, using Expert I as an example.

First, Expert I selected the most important and the least important aspects from the five aspects in the formal decision-making structure. He then assigned scores ranging from 1 to 9 according to their importance from low to high. The results are shown in Table 3.

Second, expert I selected the most and the least important factors in Aspect A and also scored the Best-to-others (BO) and others-to-worst (OW) on a scale of 1–9. The results are shown in Table 4. He applied the same process to Aspect B-E. The results are shown in Table A3-A6(Appendix).

Finally, we used model (1) in Sect. 3 to calculate the relative weights and target values. Their absolute weights were calculated, as shown in Table 5.

The work of Experts II, III, IV, and V follows the same procedure as that of Expert I. We collected the computational results and calculated the geometric mean of the results from the different experts to obtain final

Expert	Organization	Position	Duties	Seniority (yr)
I	A local environmental management bureau	Deputy director	To respond to public environmental management	9
II	A rural business affairs center	Chairman	Rural affairs management	15
III	A public administration department of the local province government	Senior technologist	Public health management	19
IV	A waste recovery and disposal (limited) company	General manager	Recovery and disposal of RSW	13
V	An agricultural research university	Professor	Front-line work of rural economy	18

Table 1. Professional backgrounds of the selected five experts.

Aspect	Criteria	Necessity Scoring					Mean Value	Standard deviation	CDI	Variable number
		I	II	III	IV	V				
Institution	Waste processing procedure standards	9	9	9	8	9	8.8	0.400	0.045	A1
	Waste sorting standards	7	8	8	8	8	7.8	0.400	0.051	A2
	Reward and punishment incentive mechanism	8	8	8	7	8	7.8	0.400	0.051	A3
	Supervision mechanism	5	5	6	6	6	5.6	0.490	0.087	Discarded
	Waste processing fee mechanism	6	6	7	7	7	6.6	0.490	0.074	A4
	Waste management subsidy mechanism	5	4	5	5	5	4.8	0.400	0.083	Discarded
	"County-Town-Village" linkage mechanism	9	9	8	9	9	8.8	0.400	0.045	A5
Personnel	Environmental governance promotion	4	4	4	4	5	4.2	0.400	0.095	Discarded
	Waste management training	8	7	8	8	8	7.8	0.400	0.051	B1
	Village leaders' initiative system	7	7	7	7	7	7	0.000	0.000	B2
	Formation of professional waste management teams	8	8	8	8	8	8	0.000	0.000	B3
Logistics	Waste sorting	9	9	9	10	9	9.2	0.400	0.043	C1
	Waste collection	6	5	5	6	6	5.6	0.490	0.087	Discarded
	Waste transportation	7	7	7	8	8	7.4	0.490	0.066	C2
	Logistics linkage management	8	8	8	9	8	8.2	0.400	0.049	C3
Processing	Optimization of fuel mix (not primarily straw)	7	8	7	7	7	7.2	0.400	0.056	D1
	Maximizing composting benefits	8	8	7	8	8	7.8	0.400	0.051	D2
	Centralized waste management	10	10	9	9	8	9.2	0.748	0.081	D3
	Diversified management approaches	10	10	9	10	10	9.8	0.400	0.041	D4
	Enhancing recycling rate	5	5	5	5	4	4.8	0.400	0.083	Discarded
	Promotion of new treatment technologies	8	8	7	8	8	7.8	0.400	0.051	D5
Support	Support for non-governmental environmental organizations	7	7	7	7	8	7.2	0.400	0.056	E1
	Expanding the sanitation market (especially the intermediary recycling market)	7	8	7	7	8	7.4	0.490	0.066	E2
	Diversified supporting funds	7	8	8	8	7	7.6	0.490	0.064	E3
	Multi-subject coordination long-term mechanism	10	9	10	9	9	9.4	0.490	0.052	E4
	Infrastructure construction	3	3	3	3	3	3	0.000	0.000	E5
	Enterprise participation (PPP Model)	8	8	8	8	9	8.2	0.400	0.049	E6
	Inclusion of diverse entities (financial institutions, research institutions, etc.)	4	5	5	5	5	4.8	0.400	0.083	Discarded
	Construction of an information-sharing platform	6	6	5	6	6	5.8	0.400	0.069	Discarded
	Urban-rural integrated operation model	9	9	10	9	9	9.2	0.400	0.043	E7
	Improving the waste recycling industrial chain	7	8	8	8	7	7.6	0.490	0.064	E8
	Improving government-centric public management	5	6	6	5	5	5.4	0.490	0.091	Discarded

Table 2. Necessity scores of criteria in the third step of scoring of the Delphi questionnaire.

BO	A	B	C	D	E
Best criterion: E	5	8	3	1	1
OW		Worst criterion: B			
A		3			
B		1			
C		6			
D		7			
E		8			

Table 3. Best-to-others (BO) and others-to-worst (OW) pairwise comparison vectors.

weights. We ranked the factors in descending order and obtained the key factors as shown in Table 6. The results showed that the first eight items were critical factors: D4, C1, E4, E7, D3, E5, E6, and C3.

Assessing the RSW management to provinces

In order to further analyze and evaluate the management of RSW in China, this paper selects representative provinces from four regions of China: Heilongjiang, Gansu, Zhejiang, and Sichuan. Heilongjiang is an old industrial base in Northeast China but has recently experienced severe outmigration in the rural areas. Zhejiang,

BO	A1	A2	A3	A4	A5
Best criterion: A5	2	8	3	6	1
OW		Worst criterion: A2			
A1		7			
A2		1			
A3		4			
A4		2			
A5		8			

Table 4. Best-to-others (BO) and others-to-worst (OW) pairwise comparison vectors: aspect A.

Aspect(weight)	ξ^L	Criterion	ξ^L	Relative weight	Composite weight
A(0.1026)	0.08547	A1	0.0698	0.25581	0.0262
		A2		0.04651	0.0048
		A3		0.17054	0.0175
		A4		0.08527	0.0087
		A5		0.44186	0.0453
B(0.0427)		B1	0.0250	0.65000	0.0278
		B2		0.12500	0.0053
		B3		0.22500	0.0096
C(0.1709)		C1	0.0370	0.70370	0.1203
		C2		0.11111	0.0190
		C3		0.18519	0.0317
D(0.2564)		D1	0.1091	0.11549	0.0296
		D2		0.04491	0.0115
		D3		0.28873	0.0740
		D4		0.46838	0.1201
		D5		0.08249	0.0212
E(0.4274)		E1	0.06664	0.05693	0.0243
		E2		0.06641	0.0284
		E3		0.03321	0.0142
		E4		0.33207	0.1419
		E5		0.13283	0.0568
		E6		0.09962	0.0426
		E7		0.19924	0.0851
		E8		0.07970	0.0341

Table 5. Weight calculation results of expert I.

located in the eastern region, is an economically developed province and the birthplace of China's e-commerce industry. Sichuan, in the southwest region, is a populous province with a high rural population ratio. The province has complex terrain and is frequently affected by natural disasters such as earthquakes, leading to an underdeveloped logistics network. Gansu Province, situated in the northwest, has a relatively lower economic level compared to the other selected provinces, a low population density, and a well-developed animal husbandry industry. These four provinces differ significantly in terms of economic development levels, industrial layout, and rural population density. By selecting these provinces as cases for study, we can compare the differences in RSW management at various stages of development and provide optimized solutions for RSW management based on key factors.

We reinvited a group of five experts familiar with the RSW management situations of the four provinces to use the formal decision-making structure (Table 2). The experts rated the RSW indicators of the four provinces using the Likert scale, and the calculated average values were used to derive the Decision Matrix, as shown in Table 7.

We normalized the above Decision Matrix and calculated the values of the group utility P_i and individual regret Q_i following the VIKOR procedures. The results are shown in Table A7(Appendix). We calculated the VIKOR index for each alternative(Ri), as shown in A8(Appendix).

We ranked the alternatives by sorting the P_i, Q_i, and Ri values in decreasing order such that the best rank is assigned to the alternative with the smallest VIKOR value. The results are three ranking lists. Table 8 presents the ranking lists for the alternatives based on the P_i, Q_i, and Ri values.

Criterion	Expert I	Expert II	Expert III	Expert IV	Expert V	Geometric mean	Normalization	Rank
D4	0.120	0.120	0.117	0.189	0.120	0.131	0.137	1
C1	0.120	0.122	0.120	0.113	0.116	0.118	0.124	2
E4	0.142	0.147	0.145	0.052	0.082	0.105	0.110	3
D3	0.074	0.070	0.070	0.118	0.075	0.080	0.098	4
E7	0.085	0.086	0.085	0.086	0.137	0.094	0.083	5
E5	0.057	0.057	0.056	0.034	0.055	0.051	0.053	6
A1	0.026	0.040	0.011	0.046	0.047	0.030	0.040	7
C3	0.032	0.032	0.034	0.043	0.044	0.037	0.038	8
E1	0.024	0.025	0.024	0.015	0.023	0.022	0.032	9
E6	0.043	0.043	0.042	0.026	0.041	0.038	0.031	10
E8	0.034	0.034	0.034	0.021	0.033	0.031	0.028	11
E2	0.028	0.029	0.028	0.017	0.027	0.026	0.027	12
D5	0.021	0.013	0.012	0.059	0.037	0.023	0.026	13
A5	0.045	0.023	0.019	0.027	0.027	0.027	0.024	14
B3	0.010	0.010	0.068	0.030	0.028	0.022	0.023	15
D1	0.030	0.023	0.023	0.018	0.011	0.020	0.023	16
B1	0.028	0.029	0.025	0.011	0.010	0.019	0.021	17
D2	0.012	0.035	0.035	0.034	0.021	0.025	0.019	18
C2	0.019	0.019	0.017	0.016	0.017	0.018	0.018	19
A3	0.017	0.004	0.007	0.018	0.018	0.011	0.013	20
E3	0.014	0.014	0.013	0.009	0.014	0.012	0.012	21
A4	0.009	0.008	0.004	0.009	0.009	0.007	0.008	22
A2	0.005	0.012	0.002	0.005	0.005	0.005	0.006	23
B2	0.005	0.005	0.010	0.005	0.004	0.006	0.005	24

Table 6. Weight and rank of Criterion.

This paper evaluates the RSW management performance of four representative provinces in China based on the constructed RSW management evaluation index system. The final performance rankings from best to worst are Zhejiang > Liaoning > Sichuan > Gansu. Zhejiang Province leads significantly in RSW management performance, while Gansu Province lags, highlighting the importance of economic development. In economically developed areas, the logistics network for RSW is relatively complete, and advanced logistics facilities provide fundamental support for RSW management. Additionally, Zhejiang Province has invested substantially in rural environmental protection and management over the past three years, making its top performance unsurprising.

Although rural areas in Liaoning Province face severe population loss, they have systematically addressed RSW issues through the "multi-subject governance" model, which ensures social participation. This model has resulted in a better performance than that of Sichuan, which has stronger economic conditions. The above finding indicates that while RSW management effectiveness is influenced by regional economic conditions, it is not entirely constrained by economic development. Comprehensive consideration of external conditions and regional issues, along with innovation in management models and targeted responses to key factors, is crucial for effective RSW management.

Discussion and implications

Discussion

This paper uses the BWM for weight calculation to rank the key influencing factors in RSW management. The top 8 key factors, in descending order of importance based on their weights, are: D4 > C1 > E4 > D3 > E7 > E5 > A1 > C3. The following conclusions can be drawn based on the identification results of the key factors:

(1) Based on the identification of key factors, it can be determined that D4, Diversified management approaches, is the factor with the highest weight, a conclusion similar to previous research findings[2]. However, from the proportional distribution of key factors, it is evident that Aspects D and E have the highest proportions among the key factors, and these factors are closely related to the "multi-subject governance" model. Whether dealing with RSW or MSW, it is crucial to recognize that waste is essentially a misplaced resource. This perspective ensures environmentally friendly and economically sustainable waste management. By employing diverse treatment methods, the potential value of waste can be deeply explored, making D4 a very reasonable key factor.

In the array of diverse treatment methods, landfilling, and incineration, despite causing some resource wastage, are fundamental measures in many countries to protect rural areas from waste pollution and should be used as the final means of RSW management under government leadership. Other treatment methods, such as recycling and biomass power generation, require the government to actively guide research institutions,

	A1	A2	A3	A4	A5	B1	B2	B3	C1	C2	C3	D1	D2	D3	D4	D5	E1	E2	E3	E4	E5	E6	E7	E8
Liaoning	3.4	3.6	4.6	2.4	2.2	3.6	4.8	2.6	3.6	4.8	3.8	3.6	3.4	4.8	2.6	3.6	3.4	3.4	2.4	3.4	4	3.6	3.8	3.4
Gansu	1.4	2.4	2.8	1	1.4	1.6	1.8	1.2	1.2	4.8	1.4	2.4	3.8	1.8	3.8	1	2.6	1.6	1.6	1.8	1.6	1.2	1.6	1
Zhejiang	4.6	4.6	3.8	3.6	4.8	3.6	3.4	4.6	3.8	4.6	3.6	4.8	2.6	4.6	3.6	3.8	3.4	3.8	4.8	3.6	4.8	4.8	4.8	3.6
Sichuan	2.8	2.8	3.4	1.6	2.6	3.6	2.4	1.6	2.6	3.4	1.2	1.8	3.6	2.6	2.4	1.6	3	2.4	1.2	2.4	1.4	2.2	3.4	2.8

Table 7. Decision Matrix for 4 provinces.

Alternatives	*P* value	Rank in *P*	Q value	Rank in Q	*R* value	Rank in *R*
Liaoning	0.117	2	0.274	2	0.559	2
Gansu	0.124	3	0.813	4	0.945	4
Zhejiang	0.02	1	0.059	1	0	1
Sichuan	0.137	4	0.69	3	0.918	3

Table 8. The ranking list for the alternatives. We conducted the conditions survey and found that Condition 1 and Condition 2 are simultaneously satisfied.

manufacturing enterprises, power companies, and even financial institutions to participate in technology development and promotion to continuously optimize RSW management effectiveness[2,47]. However, the involvement of multiple entities can easily lead to coordination failures or dishonest practices within an immature supply chain system. To address this, integrating government administrative measures and market incentive mechanisms is necessary to achieve diversified coordination, making E4(Multi-subject coordination long-term mechanism) also a critical factor in RSW management.

(2) Aspect C (Logistics) has always been the most critical aspect in MSW management[45,48], but in RSW management, only C1(Waste sorting standards)and C3(Logistics linkage management) are key factors. The reason lies in the difference between the supply chains: MSW operates with a responsive supply chain, while RSW utilizes an efficient supply chain. Due to the relatively concentrated and large-scale emissions of MSW, efficiency is crucial in its management, with the logistics system being the key determinant of processing timeliness. In contrast, RSW has lower emission volumes and concentration, making operational costs and processing efficiency the focal point of its management. C1 can reduce RSW processing costs, while C3 ensures the most cost-effective and environmentally controlled conditions through appropriate transport routes and batch processing. Thus, RSW management focuses more on C1 and C3 rather than the entire logistics system.
(3) D3(Centralized waste management), E7(Urban-rural integrated operation model), and E5(Infrastructure construction) are factors with similar weight rankings, acting as characteristic influencing factors in RSW management, differing significantly from MSW management. These three factors exhibit strong synergy. Firstly, in sparsely populated rural areas where solid waste emissions are dispersed, adopting D3 can help reduce operational costs. However, designing measures for D3 must be done with caution, as overemphasis on D3 measures can lead to significant pressure on county-level entities involved in RSW management. To address this, large-scale, high-capacity institutions with relatively simple methods may be required for RSW management. Secondly, the allocation of resources and the smooth flow of RSW during transit require calculating and predicting RSW flow volumes to plan and configure E5 and E7 accordingly.
(4) E6 (Enterprise participation) is not identified as a highly weighted key factor in MSW management as in many other studies[41], which reveals the significant differences between MSW management and RSW management. Market mechanisms are not a panacea for RSW management. The notion of "government inefficiency, market efficiency" does not apply to RSW management. Due to the dispersed pollution sources, extensive coverage, and small quantities, RSW is intertwined with agricultural production, rural livelihoods, and ecosystems. The market cannot integrate multiple subjects' participation effectively, and RSW currently lacks substantial economic value, resulting in insufficient market enthusiasm for its management.

Implications

From the above research, it can be concluded that the MSG model is an advanced and scientific management approach for RSW governance, particularly suitable for economically underdeveloped areas. Due to the lack of advanced waste treatment technologies, adequate waste treatment facilities, and an efficient waste logistics system, economically underdeveloped areas can only address the core issues of low profitability and dispersed distribution in RSW governance through the MSG model. The following section will propose measures for implementing RSW governance under the MSG model, based on the results of key factor identification and case analysis.

(1) In RSW governance, D4 (Diversified management approaches) and E4 (Multi-subject coordination long-term mechanism) are two interrelated key factors. Due to the characteristics of RSW, the development of D4 requires collaboration among waste management agencies, manufacturing enterprises, and rural residents. Waste management agencies need to adopt diversified governance methods and acquire supporting equipment; manufacturing enterprises should view waste management agencies as a crucial procurement channel for raw materials to effectively close the reverse supply chain of RSW; rural residents need to perform proper waste sorting to reduce supply chain costs.

Considering the significant proportion of public welfare actions in RSW governance, these three subjects clearly lack the motivation to implement the aforementioned actions, which means the multi-subject governance system cannot entirely rely on market coordination and must be government-led. Through multi-subject coordination long-term mechanisms (E4) such as subsidies, taxation, regulation, and administrative penalties, the government can help establish collaborative relationships among multiple subjects. In the initial stages of collaboration, the government may need to integrate research institutions and finan-

cial organizations through targeted policies to provide necessary technical and financial support for RSW governance. As the collaboration among multiple subjects gradually becomes smoother, RSW governance approaches will become more diverse and reasonable, increasing supply chain profitability. A 'ratchet effect' will emerge among the subjects, at which point the government can gradually introduce market competition mechanisms to eliminate 'stagnant' enterprises within the supply chain, thereby accelerating the optimization of the RSW supply chain.

In the early stages of RSW governance reform, attention must be paid to the principal-agent problem between the government and waste management enterprises in economically underdeveloped areas. The core objective of the government is environmental protection, while the core objective of enterprises is profit, which can lead to dishonest practices and low-quality waste management. Therefore, it is necessary to introduce supervision mechanisms among the multiple subjects and establish a comprehensive interest linkage mechanism.

(2) RSW is an efficiency-oriented supply chain; therefore, special attention must be paid to managing supply chain costs. C1 (Waste sorting standards), D3 (Centralized waste management), and C3 (Logistics linkage management) are the primary methods for reducing costs. Firstly, it is essential to conduct awareness campaigns and training for rural residents on RSW classification and the 3R actions (Reduce, Reuse, Recycle). Secondly, due to the dispersed distribution of RSW, it is necessary to encourage rural residents to organize RSW collection on a village-by-village basis. Since a majority of rural residents have ample free time and are sensitive to income, low-cost incentives can be provided to villages that achieve good results in waste classification and centralized collection, and a small portion of the subsidies previously allocated to waste management agencies can be reallocated for this purpose. For waste management agencies, centralized and properly classified RSW can significantly reduce processing costs, so a slight reduction in processing subsidies will not affect their motivation. At the same time, attention should be paid to establishing proper supervision mechanisms to avoid a vicious cycle where 'the more the government invests, the more waste is generated, and the less effective the governance becomes.' Thirdly, during the logistics linkage management process, such as temporary storage and centralization of RSW, special care must be taken to prevent well-sorted RSW from being mixed again. It is essential to reasonably design the frequency of waste collection and the logistics routes based on climate conditions and other factors to reduce logistics costs.

(3) Based on regional conditions, the E7 (Urban-rural integrated operation model) should be designed with a scientific division of labor according to waste treatment methods. A multi-subject governance model not only requires effective collaboration among enterprises involved in RSW governance but also necessitates coordination among different levels of administrative units. This is because waste management at the village and town levels typically can only handle basic landfill and burning processes. For RSW that needs to be recycled and reused, villages and towns usually lack the complete processing equipment required, necessitating the transfer and centralized treatment of RSW. Therefore, it is essential to plan the governance methods in advance based on the type of waste. It is also important to configure waste treatment facilities and select the locations for key processing nodes based on geographical proximity, thereby constructing a hierarchical RSW management system of 'village collection, town transfer, and city treatment.

Conclusion

In the current RSW governance, most countries still adopt a government-led model represented by standardization and indexation, lacking the participation of market and social forces. This model is inefficient and unsustainable. However, the characteristics of RSW lead to the lack of market interest in participating in RSW at the current technological level. To address this dilemma, this paper explores the compatibility of the "multi-subject governance" model with RSW governance and draws the following research conclusions:

This paper organizes various factors affecting RSW governance and constructs an evaluation index system for RSW within the multi-subject governance model, providing theoretical support for innovative RSW governance models.

This paper uses the Best-Worst Method (BWM) to rank the indicators affecting RSW governance effectiveness, confirming key factors such as D4 (Diversified management approaches), C1 (Waste sorting), and E4 (Multi-subject coordination long-term mechanism). It discusses the effective implementation paths of the multi-subject governance model in different rural development contexts, considering the interaction effects between key factors. The strategy emphasizes the effective management of implementation costs while focusing on the refined management of key factors.

Using four provinces in China with different characteristics as case studies, this paper evaluates the effectiveness of RSW governance, ranking the RSW performance of the four provinces from high to low as Zhejiang, Liaoning, Sichuan, and Gansu. The evaluation results indicate that RSW governance is closely related to the regional economy. However, by formulating reasonable countermeasures based on the existing conditions of regional RSW governance and combining key factors with regional bottlenecks, it is possible to construct a "multi-subject governance" model that fits regional characteristics, thereby significantly improving RSW governance effectiveness.

RSW governance is an issue that encompasses both public welfare and economic aspects influenced by comprehensive factors such as regional economy, governance technology level, and governance model. Therefore, RSW governance is a dynamic process that requires continuous optimization of governance strategies according to changes in internal and external conditions. The evaluation index system constructed in this paper is designed for the current state of RSW under existing conditions and is a static index system. Moreover, the multi-subject governance model cannot address the problems of all economies. This model is essentially a "balanced solution"

between government-led and fully market-regulated models, though it has certain application limitations. First, the implementing country must possess a high level of waste treatment technology and be capable of effectively managing MSW. The management of RSW is more complex than that of MSW; without extensive experience in MSW management, it becomes challenging to establish an effective RSW governance system. Second, the country must have a governance philosophy centered on sustainable development. The establishment of an RSW governance system, particularly in its initial stages, relies heavily on the government's coordination and management capabilities, as well as on economic incentive mechanisms. If the focus is solely on the economic benefits of RSW, there may be a lack of motivation to engage in RSW governance. Third, the model must be tailored to regional conditions and residents' living habits. For instance, in areas with significant urban-rural distances or in regions where logistics are hindered during the winter, it is essential to coordinate local RSW governance with centralized management and to enhance the construction of temporary storage facilities for valuable RSW. Therefore, the localization and integration of the multi-subject governance model will be the focus of further research.

Data availability

All data that support the findings of this study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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