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Research Article

An Approach for Resilient-Green Supplier Selection Based on WASPAS, BWM, and TOPSIS under Intuitionistic Fuzzy Sets

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The green supply chain management (GSCM) is an enterprise's effort to protect the environment and a key way to achieve sustainable environmental development. On the contrary, globalization brings more risks to the supply chain. Resilience has become a critical definition in supply chain management to help enterprises review the disruption and return to normal state. Therefore, choosing a resilient-green supplier to build a supply chain environment with flexibility and greenness under interruption becomes necessary for research works. However, the existing studies tended to focus on only one of the factors with resilience and greenness, and no comprehensive criteria system and performance value is expressed by a crisp number. Therefore, this paper proposes a hybrid method which integrates the Best-Worst method (BWM), Weighted Aggregated Sum-Product Assessment (WASPAS), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to solve the critical problems. Firstly, BWM is used to weigh the criteria; secondly, intuitionistic fuzzy numbers are introduced into the ranking stage. Then, the integrated WASPAS and TOPSIS are used to rank the alternatives to select the optimal resilient-green supplier. Finally, an illustrative example proves the feasibility of this method.

1. Introduction

With the environment adverse changes, green supply chain management (GSCM) emerged as the times when enterprises and products needed to adapt to the characteristic of resource-efficient and environment-friendly. GSCM required collaboration between the upstream and downstream enterprises in the supply chain, integrating efficient and green concepts into key nodes of product design, production, packaging, transportation, marketing, and recycling [1]. Core enterprises should be responsible not only for their own actions but also for the negative environmental impact of upstream and downstream enterprises. Therefore, the supplier selection has become the key issue of green supply chain coordination [2]. It is also a critical way for enterprises to gain competitiveness under the environment-friendly trend and policy.

Due to the globalization of the supply chain, logistics and information flow are facing the fluctuation risk brought by the disruptions, which are mainly caused by the natural disasters, man-made disasters, and technological threats. GSCM was confronted with similar problems. How to simultaneously weaken the impact of the supply chain on the environment and improve the ability to respond to disruptions has become a critical issue to be solved urgently in the supply chain management. Integrating resilient practice into the green supply chain can deal with the disaster-related uncertainty, reduce the quality fluctuation in green raw materials, and effectively avoid the logistics interruption in product transportation, marketing, and recycling.

Therefore, it is a new challenge for managers to construct the supply chain that can operate in the environment of green policy and respond to the disruptions in time when disasters occur. In the resilient-GSCM, the supplier selection is the key way to achieve the goal. At present, the relationship between the resilience and green was established in supply chain management [3–5]. Several research studies have also discussed the resilient supplier selection [6–10] and green supplier selection [1, 11–14]. However, few studies considered both the resilience and greenness factors in supplier selection problems. Thus, a decision-making method was proposed for selecting suppliers that can take both environmental problems and disruption risks for further research studies into account.

Supplier selection is a typical multicriteria group decision-making (MCGDM) problems. The MCGDM always consists of three research fields [15, 16]: expert weighting methods, criteria weighting methods, and aggregation operators. The studies of expert weighting methods and criteria weighting methods are mainly concentrating on the computation of the weights of the experts and criteria and which are often obtained by decision makers directly based on experiences and preferences [17] or worked out by the decision matrix [18–20]. The aggregation operators are mainly focused on the conversion process of the collective decision matrix to the integrated evaluate values of alternatives with the weights of the experts and criteria in various aggregation methods [21, 22], and then rank the alternatives. Scholars usually focus on one or two fields in MCGDM, and few studies researched these all three ways simultaneously in one article due to the huge amount of work, for example, some research studies only focus on criteria weighting methods [23, 24] or aggregation operators [21, 25]. Wu et al. [26] focus on both experts and criteria weighting methods. Zavadskas et al. [27] discussed the optimization of criteria weighting and aggregation operator.

Through literature review, it was found that there were several limitations in terms of the resilient-green supplier selection. Firstly, few studies focused on the resilient-green supplier selection. According to the green manufacturing process and resilience-related characteristics, the resilience-greenness criteria system was constructed; secondly, the language terms used in many MCGDM problems were not in line with the expression habits of decision makers and reduced the accuracy of decision-making process; thirdly, the traditional weighting methods (such as AHP) of MCGDM had more steps to compare, so the calculation process was more complicated; lastly, the single MCGDM method made the alternatives' ranking inaccurate and inconsistent.

Therefore, in order to fill the research gap, a novel method, which integrated WASPAS, BWM, and TOPSIS based on intuitionistic fuzzy numbers, was proposed to select the resilient-green supplier under the supply chain environment. The reasons of why we integrate these techniques in our method are mainly based on the following three ways. (1) Compared with triangle fuzzy number and trapezoid fuzzy number (only can represent one grade of membership that is crisp in the unit interval), intuitionistic fuzzy number can reflect more grades of membership, that is, membership degree, nonmembership degree, and hesitation degree [28]. The hesitation degree represents the definition of "neither this nor that" [29]. Intuitionistic fuzziness has more advantages in reflecting fuzziness and uncertainty in the decision matrix. Therefore, our research is conducted in the intuitionistic fuzzy environment. (2) BWM simplifies the calculation steps, and the weighting results are more consistent than the traditional AHP [30]. Therefore, BWM is selected as the method of criteria weighting in this study. The integrated WASPAS and TOPSIS methods make up for the instability of traditional WASPAS due to the change of parameter value, improving the accuracy and certainty of decision results [31]. Hence, we integrate BWM, WASPAS, and TOPSIS techniques to become a new MCGDM approach, which has advantages that a single classical approach does not. (3) As mentioned above, the research of MCGDM is mainly divided into three aspects, and few studies researched these entire three ways at the same time in one article due to the amount of work. In this study, we focus on the improvement of criteria weighting process, and the aggregation operators are not our focus. Hence, through literature review, we find that the intuitionistic Fuzzy Weighted Averaging (IFWA) and Intuitionistic Fuzzy Ordered Weighted Averaging (IFOWA) proposed by Xu [32] are applicable to different situations with intuitionistic fuzzy sets. Besides, IFWA is more appropriate for the research of the weighting methods for criteria in intuitionistic fuzzy sets [33]. Hence, we choose IFWA operator [32] as the aggregation operator to aggregate the decision information in this study, due to the advantages of logical [34, 35], easy to operate [36], and highly recognized [33, 37].

This paper consists of seven parts. Section 1 is an introduction, Section 2 presents the literature review, and the construction of the criteria system appears in Section 3. Section 4 introduces some basic definitions about the decision method. In Section 5, a hybrid MCGDM method is proposed, and the feasibility of the method is verified by an illustrative example in Section 7. Finally, the conclusion of the whole paper is presented in Section 8.

2. Literature Review

GSCM was part of the efforts of organizations and researchers to respond to environmental awareness and sustainable development policies [13]. The implementation of GSCM could protect the environment, save resources, and enhance the competitiveness of supply chain enterprises. Therefore, GSCM has become a more popular definition.

With the increase of public awareness and pressure from the governments, researchers paid more attention on the GSCM and much related works have been performed. For example, Handfield et al. [38] defined GSCM for the first time, incorporating environmental factors into customer orders cycle for design, procurement, manufacturing, assembly, packaging, logistics, and distribution activities. Zhu et al. [39] improved the definition and put forward that the purpose of implementing green supply chain was to help enterprises obtain profits and market share. After that scholars mainly defined the GSCM from the aspects of green practices and principles, emphasizing the integration of environmental dimension/issues into supply chain management in order to achieve environmental performance [40–44] and involving a series of green measures throughout the product's life cycle, including product design, material selection and procurement, manufacturing process, delivery of the final products, marketing, reverse logistics, and end-of-life management [45–50]. In the past two decades, many studies have focused on the green supplier evaluation and selection. Handfield et al. [51] introduced environmental factors into the supplier evaluation criteria and calculated them with the analytic hierarchy process (AHP). Tsai and Hung [52] constructed an evaluation model from the perspective of performance to help enterprises manage and monitor green supply chain. Akman [53] clustered suppliers according to criteria-delivery, quality, cost, and service by c-means clustering method and finally used VIKOR to rank the green suppliers. Lo et al. [12] constructed the criteria system of performance, environmental protection, and risk, combining MCGDM and FMOLP to solve the problem of green supplier selection and order allocation. Peng et al. [54] established evaluation criteria from three aspects of economy, environment, and society, determined the criteria weight in the picture fuzzy environment, and selected more sustainable suppliers.

Global supply chains enabling the interrelated business activities were handled around the world in a decentralized way; thus, enterprises could reduce the production costs and achieve profits by finding competitive partners [55]. In the globalization environment, natural disasters (floods and earthquakes), man-made disasters (fires, traffic accidents, and terrorist attacks), and technological threats (technology leaks) would lead to the fluctuation and interruption in supply chains [56–58]. Increasing supply chain resilient practice and choosing more resilient suppliers were effective ways to avoid the interruption. Holling [59] first proposed the concept of resilience and pointed out it was the special ability to absorb change. With the application of resilience in the supply chain, the resilient supply chain emerged as a new concept [60]. Ponomarov and Holcomb [61] defined it as "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and function." Other definition focused on the ability of enterprises to recover normal operation after interruption [62, 63]. At present, resilience could be improved from two aspects: (1) improving the supply chain (e.g., creating redundancies, increasing flexibility, and changing the corporate culture) [64] and (2) selecting resilient supplier (before, during, and after disruption) [8]. Parkouhi and Ghadikolaei [10] used the grey VIKOR method to evaluate the rating of resilient suppliers by referring to the opinions of paper industry experts, and the criteria system was constructed from four dimensions of the benefits, opportunities, costs, and risks. Rajesh and Ravi [65] determined the criteria and its subcriteria from five aspects: primary performance factors, responsiveness, risk deduction, technical support, and sustainability, then ranked resilient suppliers with the grey relational analysis method.

In the field of supply chain management, resilience and greenness have already been linked. Azevedo et al. [66] took the automobile enterprises and supply chain as the research background by using the integrated assessment model to evaluate the greenness and resilience index. The results showed that enhancing resilience was conducive to improve the supply chain competitiveness, while green practice mainly affected the environment. Sonia et al. [67] designed the supply chain by integrating the ecologically sustainability and resilience based on the carbon footprint and emission, via the usage of the fuzzy AHP, TOPSIS, and multiobjective optimization method. Fahimnia and Jabbarzadeh [68] constructed a novel multiobjective optimization model and discussed the relationship between the sustainability and resilience at the level of supply chain design. Based on the research studies of drug supply chain design, Zahiri et al. [69] proposed a new stochastic fuzzy goal programming for the problem of model uncertainty and case analysis of the Truvada supply chain in the French LGBTQ community. Mohammed et al. [4] proposed a fuzzy multiobjective programming model to achieve a resilient and green supply chain design approach, which could reduce the supply chain costs and environmental impact and, moreover, extend the value of resilience. Yavari and Zaker [5] proposed a comprehensive model of the two-layered network structure to improve the design in the resilient-green closed-loop supply chain for the power network interruption to the perishable product supply chain and ultimately expected to achieve low cost and low carbon emissions in the supply chain. However, the concept of resilient green was often used for supply chain design in different industries, with only few relevant research studies for supplier selection. As the main external risk, the supplier selection with the scientific decision-making method could effectively improve the supply chain. The disruption would hinder the green development goal, and the relevant research on resilient-green supply chain is essential.

The supplier selection belonged to the category of multicriteria group decision-making (MCGDM) problem, which was usually divided into multiattribute group decision-making (MAGDM) (solution space is discrete) and multiobjective decision-making (MODM) (solution space is continuous) [70]. MAGDM as a classic solution, included TOPSIS [71], AHP [72], Analytic Network Process (ANP) [73], VIKOR [74], BWM [30], Weighted Aggregated Sum-Product Assessment (WASPAS) [75], the decision-making trial and evaluation laboratory (DEMATEL), preference ranking organization method for enrichment evaluation (PROM-ETHEE), and the elimination and choice translating reality (ELECTRE) [76].

The recent existing studies about resilient-green supplier selection methods mainly focused on three aspects. (1) MCGDM-based methods: the comprehensive ranking of suppliers was obtained by evaluating multiple criteria of several alternatives. Common MCGDM methods included TOPSIS [77, 78], VIKOR [79], AHP [80], BWM [78], WASPAS [81], and DEMATEL [82]. (2) Artificial intelligence (AI)-based methods: this method could simulate the decision-making behavior of experts accurately by analyzing a large amount of past data through computer programs, including neural network method [83], case-based reasoning, and genetic algorithm [84]. (3) Hybrid methods: these methods supported experts to integrate any of the two methods, so as to make up for the shortcomings of the single method. For example, fuzzy BWM-VIKOR [26], fuzzy AHP-TOPSIS [85], fuzzy Entropy-TOPSIS [14], BWM-DEMATEL-TOPSIS [86], and MABAC-ELECTRE [55]. The comparison of this study with previous studies on dimensions and approaches are shown in Table 1.

Literatures review showed that there were still some limitations in the resilient-green supplier selection. (1) Resilience and greenness have been linked in the application of the supply chain. Scholars also considered that the links could promote the supply chain sustainability. However, most of the existing research studies focused on the supply chain design and lacked relevant literature to improve the resilient-green supply chain from the perspective of supplier selection. As the main source of supply chain external conflict, choosing the resilient-green supplier scientifically has become a necessary research object. (2) Decision makers' opinions were difficult to express accurately with language, which affected the accuracy of criteria weighting and alternatives ranking. (3) The single MCGDM method was difficult to improve the alternatives ranking and could not work out the consistency of result.

Therefore, a criteria system for the resilient-green supplier selection based on the literature review of the green/resilient supply chain was proposed in order to fill the research gap, which integrated BWM, WASPAS, and TOPSIS into the proposed method. BWM was used in the process of weighting the criteria weight as a foolproof method. The TOPSIS method was integrated into WASPAS with intuitionistic fuzzy sets to make the final alternative as close as possible to the positive ideal solution (PIS). Finally, the novel method's effectiveness was verified by an example.

3. The Criteria of Resilient-Green Supplier Selection

The number of studies on green supplier selection was increasing [1, 4, 12, 13, 81]. However, the previous research studies ignored the green supplier selection under the disruption environment. At present, the government's requirements for environmental protection continue to spread to various industries. The supply chain exhibits a global trend, and it is increasingly important to develop effective measures to prevent the disruption of natural disasters. In this case, construction of the criteria system for resilient-green supplier selection becomes a critical branch in supplier selection.

From the perspective of integrating production process and green supply chain practices [88], the green supplier selection criteria were proposed. Green products production mainly includes design, raw material procurement, manufacturing, distribution, marketing, recycling, life cycle management, and other processes. According to practices related to each process, it is believed that the following factors should be considered. Eco-design (design) was recognized by many scholars as a prerequisite with the purpose of reducing the negative impact on the environment [89–91], which could determine the trend of greenness of products. Green procurement (raw material procurement) reflects the environmental action taken by suppliers in response to the environmental protection [77]. The pollution production and green packing (manufacturing) are two processes in manufacturing. The control of harmful substance emissions can directly affect the greenness, while green packaging is related to the recycling logistics network. Green image (marketing), as an assessment of supplier's past efforts for environmental protection, has attracted the attention of many scholars [1, 11, 13]. Life cycle management refers to the supplier's management ability and level of each process in terms of the cost, energy use, and process design.

Considering disruption from the three aspects of before, during, and after is a comprehensive view. This paper discusses the capabilities that resilient supplier should have from the two dimensions of vulnerability and recovery to build selection metrics. Vulnerability emphasized the preparation of the system before the occurrence of disasters, and recovery referred to the absorption capacity of the system during the disaster and the recovery ability after the disaster [92, 93]. The four indicators were used to select the resilient suppliers according to [8], namely, surplus inventory (vulnerability), factory segregation (vulnerability), reliability (vulnerability), and reorganization (recovery).

In the process of building the criteria system, there is an interactive part of resilience and greenness. The criteria part as coincident criteria is proposed, which acts on the resilient-green supplier selection in three aspects. Table 2 provides a detailed description of the criteria, definition, and references of resilient-green supplier selection.

4. Preliminaries

4.1. Intuitionistic Fuzzy Set

Definition 1 (see [101]). Let $\tilde{a}$ be a fuzzy set in the universe of discourse X, and $\mu_{\tilde{a}}$ is a membership function $\mu_{\tilde{a}}\colon X \longrightarrow [0,1]$, where $\mu_{\tilde{a}}(x) \leq 1 \forall x$. Fuzzy set can be represented in the following way:

$$\tilde{a} = \left\{\langle x, \mu_{\tilde{a}}(x)\rangle\colon x \in X\right\}. \tag{1}$$

Definition 2 (see [102]). Let $\tilde{a}$ be an fuzzy set in the universe of discourse X, where $\mu_{\tilde{a}}$ is a membership function $\mu_{\tilde{a}}\colon X \longrightarrow [0,1]$, $\nu_{\tilde{a}}$ is a nonmembership function $\nu_{\tilde{a}}\colon X \longrightarrow [0,1]$, and $0 \leq \mu_{\tilde{a}} + \nu_{\tilde{a}} \leq 1$. Intuitionistic fuzzy set can be represented in the following way:

$$\tilde{a} = \left\{\langle x, \mu_{\tilde{a}}(x), \nu_{\tilde{a}}(x)\rangle\colon x \in X\right\}. \tag{2}$$

$\pi_{\tilde{a}}(x)$ is called the hesitancy degree of x to $\tilde{a}$, where $0 \leq \pi_{\tilde{a}}(x) \leq 1$. When $\pi_{\tilde{a}}(x) = 0$, the intuitionistic fuzzy set should turn into a traditional fuzzy set:

$$\pi_{\tilde{a}}(x) = 1 - \mu_{\tilde{a}}(x) - \nu_{\tilde{a}}(x). \tag{3}$$

Definition 3 (see [102]). Let $\tilde{a}$ and $\tilde{b}$ be IFSs of the universe X, and the addition and multiplication of $\tilde{a}$ and $\tilde{b}$ are as follows:

Table 1: Comparison of this study with previous studies.

Literature	Dimensions: Resilience	Dimensions: Greenness	Approach	Theme
Kuo et al. [83]		√	Artificial neural network (ANN) + data envelopment analysis (DEA) + analytic network process (ANP)	The integration results of the three methods are better than two other hybrid methods, ANN–DEA and ANP–DEA
Zouggari and Benyoucef [85]		√	Fuzzy AHP + fuzzy TOPSIS	Solving order allocation problem with fuzzy TOPSIS
Hashemi et al. [87]		√	Grey relational analysis (GRA) + analytic network process (ANP)	ANP improves the uncertainty in GRA
Hosseini and Khaled [8]	√		Classification and regression tree (CART)+ neural network (NN) + analytic hierarchy process (AHP)	Hybrid methods with different categories have better prediction resilience than single-category methods
Parkouhi and Ghadikolaei [10]	√		Analytic network process (ANP) + VIKOR	Application of grey number and fuzzy set in model
Amindoust [56]	√	√	Assurance region DEA method (AR-DEA)	Combining sustainable criteria with resilient criteria in supplier selection
Demir et al. [79]		√	VIKOR-based sorting method (VIKORSORT)	VIKORSORT can be used to sort green suppliers into the predefined ordered classes
Proposed method	√	√	BWM + fuzzy WASPAS + fuzzy TOPSIS	Introducing TOPSIS into ranking stage of WASPAS can improve the accuracy and consistency

Table 2: Criteria for resilient-green supplier selection.

Criteria of greenness	Definition	References
G_1 Eco-design	Product materials are easy to recycle and reuse, using as little material and energy as possible, thus reducing the impact on the environment	[14, 94]
G_2 Green procurement	Purchasers are trained to purchase raw materials in accordance with green principles (environmentally friendly and harmless), and purchasers can communicate with product designers in a timely manner	[78]
G_3 Pollution production	Air pollution, liquid waste, solid waste, and harmful materials produced per unit of products	[13, 95]
G_4 Green packing	Green packaging meets the 4R1D principle: reduce, reuse, reclaim, recycle and degradable	[96]
G_5 Green image	Ability to produce products in accordance with green principles and the proportion of consumers accepting green products	[1, 97]
G_6 Life cycle management	Management (cost control, process design, and energy use) of the green products life cycle including design, material selection, manufacturing, marketing, and logistics	[1]
Criteria of resilience		
S_1 Surplus inventory	Under the disruption environment, surplus inventory can make up for production interruption, which can effectively temporarily prevent supply chain breakdown	[8]
S_2 Factory segregation	Enterprises has scattered and spare factory, each factory has the same technical conditions and material reserves in order to make up for production activities quickly	[56]
S_3 Reliability	Establish good cooperative relationship with partners with recognition; enterprises can provide materials and services in time, accounts are clear and true, and disruption cost is known	[60]
S_4 Reorganization	Ability to integrate resources rapidly and reconstruct corporate culture and organization	[8]
Coincident criteria		
O_1 Logistics	Greenness: planning reasonable transport routes to reduce CO_2 emissions; setting up recycling logistics, realizing the packaging reuse, and scientifically integrating this route into delivery route; use of new-energy vehicles Resilience: change the delivery route and implement the mode of multimodal transport rapidly when the original route is impacted	[98, 99]
O_2 Warehousing	Greenness: building materials are environmentally friendly, recyclable, and do not release harmful gases; classified warehousing of different products, rational layout of warehousing space, and avoiding production circuitous transportation Resilience: the warehouse is made of antiseismic and sunscreen building materials to provide physical protection for products in the natural disasters	[100]
O_3 Cooperation commitment	Greenness: managers actively take green initiatives; signing environmental commitment among partners to form green supply chain upstream and downstream linkages Resilience: enterprises have scheduled backup suppliers and establish contract relationship with backup suppliers in time when interrupting cooperation with other suppliers	[14, 100]

$$\tilde{a} \oplus \tilde{b} = \left\{ \langle \mu_{\tilde{a}}(x) + \mu_{\tilde{b}}(x) - \mu_{\tilde{a}}(x)\mu_{\tilde{b}}(x), v_{\tilde{a}}(x)v_{\tilde{b}}(x) \rangle : x \in X \right\},$$
$$\tilde{a} \otimes \tilde{b} = \left\{ \langle \mu_{\tilde{a}}(x)\mu_{\tilde{b}}(x), v_{\tilde{a}}(x) + v_{\tilde{b}}(x) - v_{\tilde{a}}(x)v_{\tilde{b}}(x) \rangle : x \in X \right\}. \quad (4)$$

Let λ be a constant, and the algorithm for $\tilde{a}$ is as follows:

$$\lambda\tilde{a} = \left\{ \langle 1 - \left(1 - \mu_{\tilde{a}}(x)\right)^{\lambda}, \left(v_{\tilde{a}}(x)\right)^{\lambda} \rangle : x \in X \right\},$$
$$\tilde{a}^{\lambda} = \left\{ \langle \left(\mu_{\tilde{a}}(x)\right)^{\lambda}, 1 - \left(1 - v_{\tilde{a}}(x)\right)^{\lambda} \rangle : x \in X \right\}. \quad (5)$$

Definition 4. Let $\tilde{a}$ and $\tilde{b}$ be IFSs of the universe X; $d(\tilde{a}, \tilde{b})$ represents the distance measure between $\tilde{a}$ and $\tilde{b}$; $d(\tilde{a}, \tilde{b})$ must fulfil the following properties [103]:

(i) $d(\tilde{a}, \tilde{b}) \geq 0$

(ii) $d(\tilde{a}, \tilde{b}) = d(\tilde{b}, \tilde{a})$

(iii) $d(\tilde{a}, \tilde{b}) = 0$, if and only if, $\tilde{a} = \tilde{b}$

(iv) If $\tilde{a} \subseteq \tilde{b} \subseteq \tilde{c}$ then $d(\tilde{a}, \tilde{c}) \geq d(\tilde{a}, \tilde{b})$ and $d(\tilde{a}, \tilde{c}) \geq d(\tilde{b}, \tilde{c})$

Let $\tilde{a} = \{\langle x, \mu_{\tilde{a}}(x), v_{\tilde{a}}(x) \rangle : x \in X\}$ and $\tilde{b} = \{\langle x, \mu_{\tilde{b}}(x), v_{\tilde{b}}(x) \rangle : x \in X\}$, and the normalized Euclidean distance $D_{\mathrm{NE}}(\tilde{a}, \tilde{b})$ between $\tilde{a}$ and $\tilde{b}$ can be represented in the following way [104]:

$$D_{\mathrm{NE}}(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{2n} \sum_{i=1}^{n} \left[\left(\mu_{\tilde{a}}(x_i) - \mu_{\tilde{b}}(x_i)\right)^2 + \left(v_{\tilde{a}}(x_i) - v_{\tilde{b}}(x_i)\right)^2 + \left(\pi_{\tilde{a}}(x_i) - \pi_{\tilde{b}}(x_i)\right)^2 \right]}. \quad (6)$$

Definition 5. Assume there are k decision makers in the decision procedure, $\tilde{w}^* = (\tilde{w}_1^*, \tilde{w}_2^*, \ldots, \tilde{w}_k^*)$ is the weight of a group of decision makers, where $\sum_{d=1}^{k} \tilde{w}_d^* = 1$. In order to integrate all decision makers' opinion into a group decision opinion, the Intuitionistic Fuzzy Weighted Averaging (IFWA) operator can be represented in the following way [32]:

$$\begin{aligned} r_{ij} &= \mathrm{IFWA}_{\tilde{w}^*}\left(r_{ij}^{(1)}, r_{ij}^{(2)}, \ldots, r_{ij}^{(k)}\right) \\ &= \tilde{w}_1^* r_{ij}^{(1)} \oplus \tilde{w}_2^* r_{ij}^{(2)} \oplus \tilde{w}_3^* r_{ij}^{(3)} \oplus \cdots \oplus \tilde{w}_k^* r_{ij}^{(k)} \\ &= \left[1 - \prod_{d=1}^{k} \left(1 - \mu_{ij}^{d}\right)^{\tilde{w}_d^*}, \prod_{d=1}^{k} \left(v_{ij}^{d}\right)^{\tilde{w}_d^*} \right]. \end{aligned} \quad (7)$$

where $r_{ij}^{(k)}$ represents an intuitionistic performance value in kth expert matrix and r_{ij} is the intuitionistic performance value aggregated by the all experts' weights.

4.2. Best-Worst Method.

4.2. Best-Worst Method. Best-worst method was proposed by Rezaei [105], which simplified the calculation process. BWM optimizes the comparison way, turning secondary comparisons into reference comparisons. Analytic Hierarchy Process (AHP), which is similar to the BWM principle, has more $(n^2 - 5n - 6)/2$ times of comparison.

Step 1: gather experts to discuss a common set of decision criteria $(C_1, C_2, \ldots, C_m)$.

Step 2: select the best (most important) and worst (least important) criteria, respectively.

Step 3: calculate the preference of the best criterion over all the other criteria by number 1 to 9. $a_{ij} > 1$ represents i is more important than j, the importance of i to j increases as the number increases. The result is recorded as Best-to-Others:

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bm}). \quad (8)$$

Step 4: calculate the preference of all the criteria over the worst criterion by number 1 to 9, and the result is recorded as Others-to-Worst:

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{mW})^T, \quad (9)$$

where $a_{ii} = 1$

Step 5: compute the optimal criteria weight by the following formula:

$$\begin{aligned} &\text{s.t.} \\ &\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, \quad \text{for all } j, \\ &\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi, \quad \text{for all } j, \\ &\sum_j w_j = 1, w_j \geq 0, \quad \text{for all } j. \end{aligned} \quad (10)$$

By solving the above inequalities, the final criteria weight $w_j = (w_1, w_2, \ldots, w_m)$ was obtained.

4.3. WASPAS Method. WASPAS method was proposed by Chakraborty and Zvadskas in 2004, which was a dominant MCGDM method integrating the weighted sum model (WSM) and weighted product model (WPM) [75]. Compared with WSM and WPM, WASPAS could provide more accurate results and simplify the calculation process [106], so it has become a more efficient tool for dealing with MCGDM problems. Assuming that w_j is weight of jth criterion, x_{ij} denotes the performance value of i th alternative according to the j th criterion ($i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$). The WASPAS method steps are as follows:

Step 1: calculate the linear normalization of performance values as follows:

$$\overline{x}_{ij} = \begin{cases} \dfrac{x_{ij}}{\max_i x_{ij}}, & \text{if } j \in C_b, \\ \dfrac{\min_i x_{ij}}{x_{ij}}, & \text{if } j \in C_n, \end{cases} \tag{11}$$

where C_b and C_n are the sets of the beneficial and nonbeneficial criteria.

Step 2: compute the measures of WSM ($Q_i^{(1)}$) and WPM ($Q_i^{(2)}$) for each alternative as follows:

$$Q_i^{(1)} = \sum_{j=1}^{m} w_j \overline{x}_{ij}, \tag{12}$$

$$Q_i^{(2)} = \prod_{j=1}^{m} \left(\overline{x}_{ij}\right)^{w_j}. \tag{13}$$

Step 3: obtain the aggregated measures of the WASPAS method for each alternative as follows:

$$Q_i = \lambda Q_i^{(1)} + (1-\lambda) Q_i^{(2)}, \tag{14}$$

where λ represents the parameter of the WASPAS method and $\lambda \in [0,1]$. When $\lambda = 1$, the WASPAS method is transformed to WSM, and $\lambda = 0$; it is transformed to WPM.

Step 4: rank the alternatives according to decreasing values of Q_i.

4.4. TOPSIS Method. TOPSIS was proposed by Hwang and Yoon [71], as a classical MCGDM problem processing method. Its principle is to make the final solution as close as possible to PIS (positive ideal solution) and away from NIS (negative ideal solution). The TOPSIS method steps are as follows:

Step 1: normalize the decision matrix as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{n} x_{kj}^2}}, \tag{15}$$

where x_{ij} is the performance value (crisp number) in decision matrix and r_{ij} denotes the normalized value, $i \in \{1, 2, \ldots, n\}$ and $j \in \{1, 2, \ldots, m\}$.

Step 2: aggregate the criteria weights to the normalized matrix by the following:

$$v_{ij} = w_j r_{ij}. \tag{16}$$

Step 3: obtain the v_j^+ (PIS) and v_j^- (NIS) for each criterion as follows:

$$v_j^+ = \begin{cases} \max\left\{v_{1j}, v_{2j}, \ldots, v_{nj}\right\}, & \text{if } j \in C_b, \\ \min\left\{v_{1j}, v_{2j}, \ldots, v_{nj}\right\}, & \text{if } j \in C_n, \end{cases} \tag{17}$$

$$v_j^- = \begin{cases} \max\left\{v_{1j}, v_{2j}, \ldots, v_{nj}\right\}, & \text{if } j \in C_b, \\ \max\left\{v_{1j}, v_{2j}, \ldots, v_{nj}\right\}, & \text{if } j \in C_n, \end{cases} \tag{18}$$

where C_b and C_n are the sets of the beneficial and nonbeneficial criteria.

Step 4: compute the separation measures for each alternative as follows:

$$\begin{aligned} S_i^+ &= \sqrt{\sum_{j=1}^{m} \left(v_j^+ - v_{ij}\right)^2}, \quad i = 1, 2, \ldots, n, \\ S_i^- &= \sqrt{\sum_{j=1}^{m} \left(v_j^- - v_{ij}\right)^2}, \quad i = 1, 2, \ldots, n. \end{aligned} \tag{19}$$

Step 5: obtain the closeness coefficient of each alternative to the ideal solution as follows:

$$\mathrm{CC}_i = \frac{S_i^-}{S_i^- + S_i^+}, \tag{20}$$

where the value of CC_i is bigger and the alternative A_i is better.

5. The Proposed Method

The proposed method consists of the following three steps: (1) Preparation stage: It constructs the decision-making group to determine the criteria, alternatives, and intuitionistic fuzzy set. After that each expert establishes the fuzzy decision matrix. (2) Computation stage: weigh the criteria by the BWM method after the discussion of experts. Then, aggregate the priori given expert weights into the fuzzy decision matrix by the IFWA operator. (3) Selection stage: after calculating the WASPAS measures of each alternative, the fuzzy TOPSIS is integrated into this step. Fuzzy positive/negative ideal solutions are computed; finally, the closeness coefficient of each alternatives is obtained. Figure 1 represents the conceptual framework of the proposed method.

Suppose that there are a set of n alternatives $(A_1, A_2, \ldots, A_n)$, a set of m criteria $(C_1, C_2, \ldots, C_m)$, and a set of k decision makers $(D_1, D_2, \ldots, D_k)$. The proposed method is as follows:

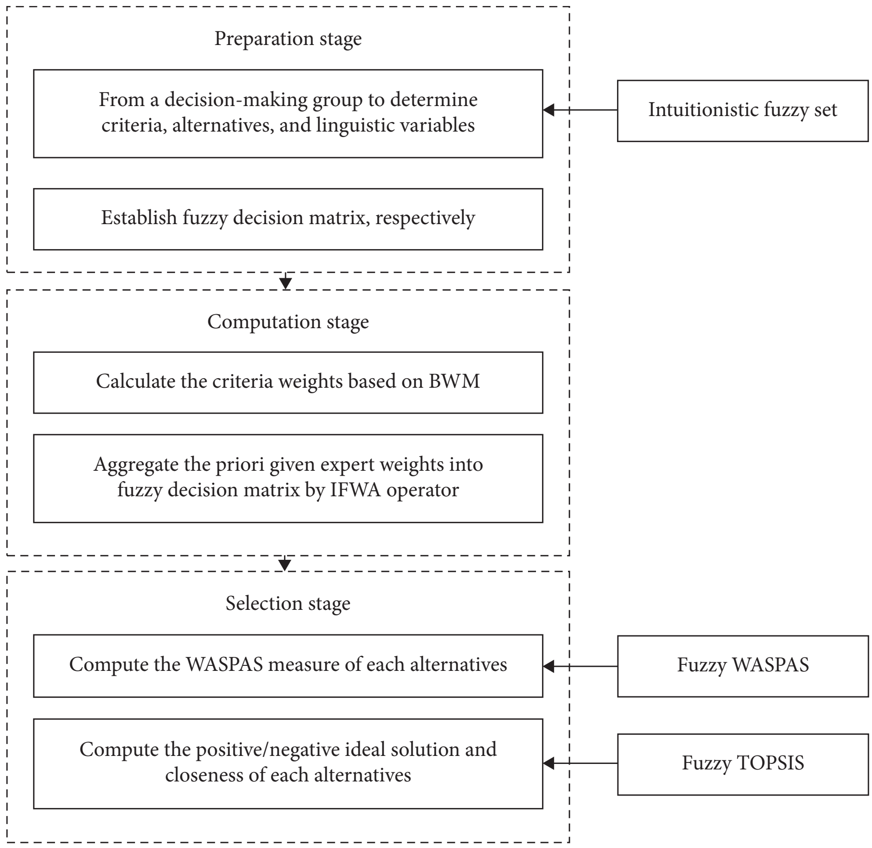

Figure 1: The conceptual framework of the proposed method.

Step 1: a group of decision makers select the best (most important) and worst (least important) criteria after discussion.

Step 2: calculate the Best-to-Others and Others-to-Worst by number 1 to 9:

$$\begin{aligned} A_B &= (a_{B1}, a_{B2}, \ldots, a_{Bm}), \\ A_W &= (a_{1W}, a_{2W}, \ldots, a_{mW})^T. \end{aligned} \tag{21}$$

Step 3: compute the optimal criteria weight by equation (10) and obtain

$$w_j^* = (w_1^*, w_2^*, \ldots, w_m^*). \tag{22}$$

Step 4: construct the fuzzy decision matrix $\mathrm{DM}^{(d)}$ of the dth decision maker as follows:

$$\mathrm{DM}^{(d)} = \left(\tilde{x}_{ij}^d\right)_{n\times m} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_m \end{array} \\ \begin{bmatrix} \tilde{x}_{11}^d & \tilde{x}_{12}^d & \ldots & \tilde{x}_{1m}^d \\ \tilde{x}_{21}^d & \tilde{x}_{22}^d & \ldots & \tilde{x}_{2m}^d \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1}^d & \tilde{x}_{n2}^d & \ldots & \tilde{x}_{nm}^d \end{bmatrix} \end{array}, \quad d = 1, \ldots, k, \tag{23}$$

where $\tilde{x}_{ij}^d$ is an intuitionistic fuzzy set, and it denotes the performance value of the alternative A_i on the criterion C_j by decision maker D_d, $1 \le i \le n$, $1 \le j \le m$, and $1 \le d \le k$. In addition, experts use the linguistic terms [107] to evaluate the alternatives as shown in Table 3.

Step 5: aggregate the decision group weights $\tilde{w}^* = (\tilde{w}_1^*, \tilde{w}_2^*, \ldots, \tilde{w}_k^*)$ into the fuzzy decision matrix $\mathrm{DM}^{(d)}$ by the IFWA operator in equation (7) and obtain the fuzzy average decision matrix DM, where $\sum_{d=1}^k \tilde{w}_d^* = 1$:

$$\mathrm{DM} = \left(\tilde{x}_{ij}\right)_{n\times m} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_m \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \ldots & \tilde{x}_{1m} \\ \tilde{x}_{21} & \tilde{x}_{22} & \ldots & \tilde{x}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \ldots & \tilde{x}_{nm} \end{bmatrix} \end{array}, \tag{24}$$

where $\tilde{x}_{ij}$ is an intuitionistic fuzzy set, and it represents the average performance value of the alternative A_i on the criterion C_j by all decision makers, $1 \le i \le n$, $1 \le j \le m$.

Step 6: calculate the normalized performance values by the following equation:

Table 3: Linguistic terms and corresponding IFNs.

Linguistic terms	Intuitionistic fuzzy numbers (μ, ν)
Extremely good (EG)	(1.00, 0.00)
Very very good (VVG)	(0.90, 0.10)
Very good (VG)	(0.80, 0.10)
Good (G)	(0.70, 0.20)
Medium good (MG)	(0.60, 0.30)
Fair (F)	(0.50, 0.40)
Medium poor (MP)	(0.40, 0.50)
Poor (P)	(0.25, 0.60)
Very poor (VP)	(0.10, 0.75)
Very very poor (VVP)	(0.10, 0.90)

$$\tilde{s}_{ij}\begin{cases}\dfrac{\tilde{x}_{ij}}{\max_i \tilde{x}_{ij}}=\dfrac{\left(u_{ij}, v_{ij}\right)}{\left(\max_i u_{ij}, \min_i v_{ij}\right)}, & \text{if } j \in C_b,\\[2ex] \dfrac{\min_i \tilde{x}_{ij}}{\tilde{x}_{ij}}=\dfrac{\left(\min_j u_{ij}, \max_i v_{ij}\right)}{\left(u_{ij}, v_{ij}\right)}, & \text{if } j \in C_n,\end{cases} \tag{25}$$

and the normalized fuzzy decision matrix $\overline{\text{DM}}$ can be obtained:

$$\overline{\text{DM}}=\left(\tilde{s}_{ij}\right)_{n\times m}=\begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \ldots & C_m \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_n \end{array} & \begin{bmatrix} \tilde{s}_{11} & \tilde{s}_{12} & \ldots & \tilde{s}_{1m} \\ \tilde{s}_{21} & \tilde{s}_{22} & \ldots & \tilde{s}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{s}_{n1} & \tilde{s}_{n2} & \ldots & \tilde{s}_{nm} \end{bmatrix} \end{array}, \tag{26}$$

where $\tilde{s}_{ij}$ denotes the normalized performance value and C_b and C_n are the sets of the beneficial and nonbeneficial criteria.

Step 7: compute the measures of WSM ($\tilde{Q}_i^{(1)}$) for each alternative in equation (12) as follows:

$$\begin{aligned}\tilde{Q}_i^{(1)} &= \sum_{j=1}^{m} w_j^* \tilde{s}_{ij} = \tilde{Q}_{i1}^{(1)} \oplus \tilde{Q}_{i2}^{(1)} \oplus \cdots \oplus \tilde{Q}_{im}^{(1)} \\ &= \left(w_1^* \otimes \tilde{s}_{i1}\right) \oplus \left(w_2^* \otimes \tilde{s}_{i2}\right) \oplus \cdots \oplus \left(w_m^* \otimes \tilde{s}_{im}\right),\end{aligned} \tag{27}$$

where w_j^* represents average weight of the jth criterion from all decision makers.

Step 8: calculate the measures of WPM ($\tilde{Q}_i^{(2)}$) for each alternative in equation (13) as follows:

$$\tilde{Q}_i^{(2)} = \prod_{j=1}^{m} \left(\tilde{s}_{ij}\right)^{w_j^*} = \tilde{Q}_{i1}^{(2)} \otimes \tilde{Q}_{i2}^{(2)} \otimes \cdots \otimes \tilde{Q}_{im}^{(2)} = \left(\tilde{s}_{i1}\right)^{w_1^*} \otimes \left(\tilde{s}_{i2}\right)^{w_2^*} \otimes \cdots \otimes \left(\tilde{s}_{im}\right)^{w_m^*}. \tag{28}$$

Step 9: obtain the WASPAS measures of each alternative by the result of steps 7 and 8:

$$\tilde{Q}_i = \lambda \tilde{Q}_i^{(1)} + (1-\lambda)\tilde{Q}_i^{(2)}, \tag{29}$$

where criterion C_j of alternative A_i measure as follows:

$$\tilde{Q}_{ij} = \lambda \tilde{Q}_{ij}^{(1)} + (1-\lambda)\tilde{Q}_{ij}^{(2)}, \tag{30}$$

where λ is the parameter of the method and $\lambda \in [0, 1]$.

Step 10: after constructing the decision matrix in the WASPAS method, the TOPSIS method is investigated in this step. Fuzzy positive/negative ideal solution ($\tilde{v}_j^+/\tilde{v}_j^-$) are obtained based on equations (17) and (18) as follows:

$$\tilde{v}_j^+ = \begin{cases} \max\left\{\tilde{Q}_{1j}, \tilde{Q}_{2j}, \ldots, \tilde{Q}_{nj}\right\} = \left(\max\limits_j u_{ij}, \min\limits_j v_{ij}\right) = \left(u_j^+, v_j^+\right), & \text{if } j \in C_b, \\ \min\left\{\tilde{Q}_{1j}, \tilde{Q}_{2j}, \ldots, \tilde{Q}_{nj}\right\} = \left(\min\limits_j u_{ij}, \max\limits_j v_{ij}\right) = \left(u_j^+, v_j^+\right), & \text{if } j \in C_n, \end{cases} \tag{31}$$

$$\tilde{v}_j^- = \begin{cases} \min\left\{\tilde{Q}_{1j}, \tilde{Q}_{2j}, \ldots, \tilde{Q}_{nj}\right\} = \left(\min\limits_j u_{ij}, \max\limits_j v_{ij}\right) = \left(u_j^-, v_j^-\right), & \text{if } j \in C_b, \\ \max\left\{\tilde{Q}_{1j}, \tilde{Q}_{2j}, \ldots, \tilde{Q}_{nj}\right\} = \left(\max\limits_j u_{ij}, \min\limits_j v_{ij}\right) = \left(u_j^-, v_j^-\right), & \text{if } j \in C_n. \end{cases} \tag{32}$$

Step 11: compute the distance from each alternative to $\tilde{v}_j^+/\tilde{v}_j^-$ according to equation (6) as follows:

$$D_i^+ = D\left(\tilde{v}_j^+, \tilde{Q}_{ij}\right) = \sqrt{\frac{1}{2m}\sum_{j=1}^{m}\left[\left(\mu_j^+ - \mu_{ij}\right)^2 + \left(v_j^+ - v_{ij}\right)^2 + \left(\pi_j^+ - \pi_{ij}\right)^2\right]}, \tag{33}$$

$$D_i^- = D\left(\tilde{v}_j^-, \tilde{Q}_{ij}\right) = \sqrt{\frac{1}{2m}\sum_{j=1}^{m}\left[\left(\mu_j^- - \mu_{ij}\right)^2 + \left(v_j^- - v_{ij}\right)^2 + \left(\pi_j^- - \pi_{ij}\right)^2\right]}, \tag{34}$$

where D_i^+ denotes the distance between the alternative A_i and the positive ideal solution $\tilde{v}_j^+$.

Step 12: calculate the closeness coefficient of each alternative to the ideal solution as follows:

$$\mathrm{CC}_i = \frac{D_i^-}{D_i^- + D_i^+}, \tag{35}$$

where the higher value of CC_i represents that the ith alternative is better.

6. Comparing the Proposed Approach with Other Methods

WASPAS, integrating the WAM and WPM model, has the advantage of higher accuracy. In addition, the WASPAS overcomes the complex multiplication calculation and becomes a convenient MCGDM method. However, through previous studies, it was found that the improved accuracy of ranking value and uncertain expression of performance value were usually ignored in the application of WASPAS and weighting the criteria was also complex. By improving some typical hybrid methods, the ranking value accuracy is increased. The hesitancy is taken into decision matrix, and a concise method to calculate criteria weight is chosen.

The main differences between the hybrid method proposed in this paper and other related methods are as follows. (1) WASPAS and TOPSIS are integrated to improve accuracy in the ranking stage so that the alternatives ranking results are closer to the decision makers' idea. (2) Intuitionistic fuzzy sets are used in the process to provide experts with freedom to express the hesitation, and it is another dimension besides the affirmation and negation. (3) The determination of criteria weights is simpler and clearer. Compared with the classical comparison method, BWM can simplify the steps and reduce the computational difficulty.

7. Illustrative Examples and Discussion

7.1. Illustrative Example. In this paper, H company's resilient-green supplier selection in supply chain environment was taken as an example. Assuming that three decision makers (d_1, d_2, d_3) evaluate four alternatives (suppliers) (A_1, A_2, A_3, A_4), H company provided three decision makers' weights (0.3, 0.3, 0.4) according to different functions. Each decision matrix must contain all the indicators, including G_1-eco-design, G_2-green procurement, G_3-pollution production, G_4-green Packing, G_5-green image, G_6-life cycle management, S_1-surplus inventory, S_2-factory segregation, S_3-reliability, S_4-reorganization, O_1-logistics, O_2-warehousing, and O_3-cooperation commitment.

Step 1. Decision makers consult to select the most important (G_3) and least important (O_2) criteria, respectively.

Step 2. Calculate the Best-to-Others and Others-to-Worst by number 1 to 9, as shown in Tables 4 and 5:

$$\begin{aligned} A_B &= (6, 5, 1, 7, 4, 2, 3, 4, 6, 7, 2, 8, 4), \\ A_W &= (5, 4, 8, 4, 6, 7, 7, 7, 5, 6, 8, 1, 5)^T. \end{aligned} \tag{36}$$

Step 3. Obtain the optimal criteria weight by equation (10):

$$w_j^* = (0.085, 0.03, 0.244, 0.028, 0.063, 0.089, 0.085, 0.089, 0.041, 0.063, 0.112, 0.022, 0.049). \tag{37}$$

Step 4. The three experts construct the decision matrix separately. The linguistic terms used in the matrix are shown in Table 3:

Table 4: Pairwise comparison vector for the best criterion.

Criteria	G_1	G_2	G_3	G_4	G_5	G_6	S_1	S_2	S_3	S_4	O_1	O_2	O_3
Best criterion G_3	6	5	1	7	4	2	3	4	6	7	2	8	4

Table 5: Pairwise comparison vector for the worst criterion.

Criteria	G_1	G_2	G_3	G_4	G_5	G_6	S_1	S_2	S_3	S_4	O_1	O_2	O_3
Worst criterion O_2	5	4	8	4	6	7	7	7	5	6	8	1	5

$$
\begin{aligned}
\mathrm{DM}^{(1)} &= \begin{bmatrix} EG & VG & F & MP & VG & VP & VVG & VG & F & VVG & MG & G & VP \\ VG & MG & G & F & MG & P & EG & VG & VG & VVP & MP & VG & P \\ EG & EG & MP & VG & G & G & G & VVG & P & MP & F & P & VP \\ G & F & P & G & MP & F & EG & F & VVP & G & F & MP & VVP \end{bmatrix}, \\
\mathrm{DM}^{(2)} &= \begin{bmatrix} MG & MP & P & G & F & P & VG & EG & MP & F & VP & MG & F \\ G & F & VP & MG & G & VVG & MG & F & VG & G & VVP & G & G \\ VG & F & MP & EG & VG & MP & P & VVG & F & P & F & VG & P \\ G & VG & VVP & VG & F & F & VG & MG & G & MP & G & G & VP \end{bmatrix}, \\
\mathrm{DM}^{(3)} &= \begin{bmatrix} VP & F & MP & MG & VVG & VP & MP & EG & F & MG & F & P & MG \\ P & VG & VG & MP & EG & F & VG & VG & G & G & VVG & MP & VG \\ F & G & F & P & VG & G & F & F & G & P & MG & VVP & F \\ VVP & VVG & VP & G & F & P & VP & VVG & VG & F & EG & VP & MG \end{bmatrix},
\end{aligned}
\tag{38}
$$

where linguistic terms can be transferred to the intuitionistic fuzzy numbers by Table 3.

Step 5. Aggregate the decision group weights $\widetilde{w}^* = (0.3, 0.3, 0.4)$ into the fuzzy decision matrix $\mathrm{DM}^{(d)}$ by IFWA operator in equation (7), and obtain the fuzzy average decision matrix DM as follows:

$$
\mathrm{DM} = \begin{bmatrix} (1,0) & (0.6,0.28) & (0.39,0.49) & (0.59,0.31) & (0.8,0.15) & (0.15,0.7) & (0.75,0.19) & (1,0) & (0.47,0.43) & (0.72,0.24) & (0.44,0.44) & (0.53,0.35) & (0.45,0.43) \\ (0.62,0.25) & (0.68,0.21) & (0.65,0.23) & (0.5,0.4) & (1,0) & (0.65,0.3) & (1,0) & (0.74,0.15) & (0.77,0.13) & (0.58,0.31) & (0.67,0.31) & (0.65,0.23) & (0.66,0.21) \\ (1,0) & (1,0) & (0.44,0.46) & (1,0) & (0.77,0.12) & (0.63,0.26) & (0.52,0.37) & (0.81,0.17) & (0.54,0.34) & (0.3,0.57) & (0.54,0.36) & (0.46,0.41) & (0.33,0.55) \\ (0.53,0.37) & (0.8,0.15) & (0.15,0.74) & (0.73,0.16) & (0.47,0.43) & (0.41,0.47) & (1,0) & (0.75,0.21) & (0.65,0.24) & (0.55,0.35) & (1,0) & (0.43,0.45) & (0.35,0.55) \end{bmatrix},
\tag{39}
$$

where

$$
\begin{aligned}
\widetilde{x}_{12} &= \left[1 - \prod_{d=1}^{3} \left(1 - \mu_{ij}^{d}\right)^{\widetilde{w}_d^*}, \prod_{d=1}^{3} \left(v_{ij}^{d}\right)^{\widetilde{w}_d^*}\right] \\
&= \left[1 - (1-0.8)^{0.3} * (1-0.4)^{0.3} * (1-0.5)^{0.4}, (0.1)^{0.3} \right. \\
&\quad \left. * (0.5)^{0.3} * (0.4)^{0.4}\right] \\
&= (0.6, 0.28).
\end{aligned}
\tag{40}
$$

Step 6. Normalize the performance values by equation (24), and the normalized fuzzy decision matrix $\overline{\mathrm{DM}}$ is obtained. Table 6 contains performance values in the $\overline{\mathrm{DM}}$.

Step 7. Compute the measures of WSM ($\widetilde{Q}_{ij}^{(1)}$) and WPM ($\widetilde{Q}_{ij}^{(2)}$) for each criterion C_j of alternative A_i by equations (27) and (28). Tables 7 and 8 represent the WSM and WPM measures of each performance value, respectively.

$$
\widetilde{Q}_{12}^{(2)} = \left(\widetilde{s}_{i2}\right)^{w_2^*} = (0.6, 0.28)^{0.03} = (0.985, 0.01).
\tag{41}
$$

Step 8. According to equation (30), the WASPAS measures are obtained, as shown in Table 9, and $\lambda = 0.5$ is set in this paper:

Table 6: The normalized performance values in the average decision matrix.

Criteria	A_1	A_2	A_3	A_4
G_1	(1, 0)	(0.617, 0.252)	(1, 0)	(0.534, 0.365)
G_2	(0.599, 0.282)	(0.676, 0.211)	(1, 0)	(0.8, 0.152)
G_3	(0.393, 0.494)	(0.645, 0.225)	(0.442, 0.457)	(0.148, 0.741)
G_4	(0.586, 0.31)	(0.497, 0.4)	(1, 0)	(0.734, 0.163)
G_5	(0.8, 0.152)	(1, 0)	(0.774, 0.123)	(0.472, 0.428)
G_6	(0.148, 0.7)	(0.652, 0.298)	(0.631, 0.26)	(0.412, 0.47)
S_1	(0.748, 0.19)	(1, 0)	(0.516, 0.367)	(1, 0)
S_2	(1, 0)	(0.737, 0.152)	(0.81, 0.174)	(0.754, 0.211)
S_3	(0.472, 0.428)	(0.765, 0.132)	(0.54, 0.342)	(0.645, 0.238)
S_4	(0.718, 0.235)	(0.583, 0.314)	(0.299, 0.568)	(0.547, 0.347)
O_1	(0.442, 0.443)	(0.67, 0.313)	(0.543, 0.357)	(1, 0)
O_2	(0.528, 0.351)	(0.65, 0.234)	(0.457, 0.412)	(0.427, 0.447)
O_3	(0.455, 0.431)	(0.664, 0.211)	(0.326, 0.546)	(0.35, 0.55)

$\tilde{s}_{12} = (\tilde{x}_{12}/\max_1 \tilde{x}_{12}) = (0.6, 0.28)/(1, 0) = (0.6, 0.28)$.

Table 7: The WSM measures of each performance value.

Criteria	A_1	A_2	A_3	A_4
G_1	(1, 0)	(0.078, 0.89)	(1, 0)	(0.063, 0.918)
G_2	(0.027, 0.963)	(0.033, 0.954)	(1, 0)	(0.047, 0.945)
G_3	(0.115, 0.842)	(0.223, 0.695)	(0.133, 0.826)	(0.038, 0.93)
G_4	(0.024, 0.968)	(0.019, 0.975)	(1, 0)	(0.036, 0.951)
G_5	(0.096, 0.888)	(1, 0)	(0.089, 0.876)	(0.039, 0.948)
G_6	(0.014, 0.969)	(0.09, 0.898)	(0.085, 0.887)	(0.046, 0.935)
S_1	(0.111, 0.868)	(1, 0)	(0.06, 0.918)	(1, 0)
S_2	(1, 0)	(0.112, 0.846)	(0.137, 0.856)	(0.117, 0.871)
S_3	(0.026, 0.966)	(0.058, 0.92)	(0.031, 0.957)	(0.042, 0.943)
S_4	(0.077, 0.913)	(0.054, 0.93)	(0.022, 0.965)	(0.049, 0.936)
O_1	(0.063, 0.913)	(0.117, 0.878)	(0.084, 0.891)	(1, 0)
O_2	(0.016, 0.977)	(0.023, 0.969)	(0.013, 0.981)	(0.012, 0.982)
O_3	(0.029, 0.96)	(0.052, 0.927)	(0.019, 0.971)	(0.021, 0.971)

Table 8: The WPM measures of each performance value.

Criteria	A_1	A_2	A_3	A_4
G_1	(1, 0)	(0.96, 0.024)	(1, 0)	(0.948, 0.038)
G_2	(0.985, 0.01)	(0.988, 0.007)	(1, 0)	(0.993, 0.005)
G_3	(0.796, 0.153)	(0.898, 0.062)	(0.819, 0.138)	(0.627, 0.281)
G_4	(0.985, 0.01)	(0.981, 0.014)	(1, 0)	(0.991, 0.005)
G_5	(0.986, 0.01)	(1, 0)	(0.984, 0.008)	(0.954, 0.035)
G_6	(0.844, 0.102)	(0.963, 0.031)	(0.96, 0.026)	(0.924, 0.055)
S_1	(0.976, 0.018)	(1, 0)	(0.945, 0.038)	(1, 0)
S_2	(1, 0)	(0.973, 0.015)	(0.981, 0.017)	(0.975, 0.021)
S_3	(0.97, 0.023)	(0.99, 0.006)	(0.975, 0.017)	(0.982, 0.011)
S_4	(0.979, 0.017)	(0.967, 0.024)	(0.927, 0.052)	(0.963, 0.027)
O_1	(0.913, 0.063)	(0.956, 0.041)	(0.934, 0.048)	(1, 0)
O_2	(0.986, 0.01)	(0.991, 0.006)	(0.983, 0.012)	(0.982, 0.013)
O_3	(0.962, 0.027)	(0.98, 0.012)	(0.947, 0.038)	(0.95, 0.038)

$\tilde{Q}_{12}^{(1)} = (w_2^* \otimes \tilde{s}_{12}) = 0.03 \otimes (0.6, 0.28) = (0.027, 0.962)$.

Table 9: The WASPAS measures of each performance value.

Criteria	A_1	A_2	A_3	A_4
G_1	(1, 0)	(0.808, 0.146)	(1, 0)	(0.779, 0.187)
G_2	(0.879, 0.098)	(0.892, 0.082)	(1, 0)	(0.918, 0.069)
G_3	(0.575, 0.359)	(0.719, 0.208)	(0.604, 0.338)	(0.401, 0.511)
G_4	(0.879, 0.098)	(0.864, 0.117)	(1, 0)	(0.907, 0.069)
G_5	(0.888, 0.094)	(1, 0)	(0.879, 0.084)	(0.79, 0.182)
G_6	(0.608, 0.314)	(0.817, 0.167)	(0.809, 0.152)	(0.731, 0.227)
S_1	(0.854, 0.125)	(1, 0)	(0.773, 0.187)	(1, 0)
S_2	(1, 0)	(0.845, 0.113)	(0.872, 0.12)	(0.851, 0.135)
S_3	(0.829, 0.149)	(0.903, 0.074)	(0.844, 0.128)	(0.869, 0.102)
S_4	(0.861, 0.125)	(0.823, 0.15)	(0.733, 0.224)	(0.812, 0.159)
O_1	(0.715, 0.24)	(0.803, 0.19)	(0.754, 0.207)	(1, 0)
O_2	(0.883, 0.099)	(0.906, 0.076)	(0.871, 0.109)	(0.867, 0.113)
O_3	(0.808, 0.161)	(0.862, 0.106)	(0.772, 0.192)	(0.779, 0.192)

$$v_j^+ = \begin{cases} \max\{v_{1j}, v_{2j}, \ldots, v_{nj}\}, & \text{if } j \in C_b, \\ \min\{v_{1j}, v_{2j}, \ldots, v_{nj}\}, & \text{if } j \in C_n. \end{cases} \tag{42}$$

For example,

$$\widetilde{Q}_{12} = 0.5\widetilde{Q}_{12}^{(1)} + (1-0.5)\widetilde{Q}_{12}^{(2)} = 0.5 \otimes (0.027, 0.963) \oplus 0.5 \otimes (0.985, 0.01) = (0.881, 0.098). \tag{43}$$

Step 9. Fuzzy positive/negative ideal solutions $(\widetilde{v}_j^+/\widetilde{v}_j^-)$ from Table 9 are obtained based on equations (31) and (32) as follows:

$$\begin{aligned} \widetilde{v}_j^+ &= \max\{\widetilde{Q}_{1j}, \widetilde{Q}_{2j}, \ldots, \widetilde{Q}_{nj}\} = \left(\max_j u_{ij}, \min_j v_{ij}\right) \\ &= \left(u_j^+, v_j^+\right), \\ \widetilde{v}_j^- &= \min\{\widetilde{Q}_{1j}, \widetilde{Q}_{2j}, \ldots, \widetilde{Q}_{nj}\} = \left(\min_j v_{ij}, \max_j u_{ij}\right) \\ &= \left(u_j^-, v_j^-\right), \end{aligned} \tag{44}$$

the $\widetilde{v}_j^+/\widetilde{v}_j^-$ from four alternatives under each criterion are represented in Table 10.

Step 10. According to Table 10 and equations (33) and (34), the distance between each alternative to positive/negative ideal solution $(\widetilde{v}_j^+/\widetilde{v}_j^-)$ is calculated. Finally, obtain the closeness coefficient for ranking four alternatives. Relevant values are shown in Table 11.

According to Table 11, the alternatives are ranked as $A_2 > A_3 > A_4 > A_1$.

7.2. Sensitivity Analysis. In the WASPAS method, λ represents the parameter and $\lambda \in [0, 1]$. How does the value of λ affect the final order of suppliers? In order to solve the problems, the sensitivity analysis was provided. We assign different values to λ, then calculate the distance between each alternative to positive/negative ideal solution $(\widetilde{v}_j^+/\widetilde{v}_j^-)$ and closeness coefficient under different conditions, so as to better carry out sensitivity analysis. The results of each alternative with different values of λ are shown in Table 12.

The second supplier is always considered to be the best choice, and the first supplier performs poorly in any case. There are two special cases. when $\lambda = 0.8$, the third supplier is superior to the second and becomes the best. When $\lambda = 0.9$, A_2, A_3, and A_4 these three suppliers are almost the same good.

7.3. Comparative Analysis. As a classical research field, there are many techniques for dealing with MCGDM problems, including TOPSIS [71], AHP [72], ANP [73], VIKOR [74], BWM [30], WASPAS [75], DEMATEL, PROM-ETHEE, and the ELECTRE [76]. In order to prove the feasibility and practicability of the method proposed in this paper, we compare the alternative ranking obtained in the above illustrative example with the results of the classical MCGDM methods. Through literature review, we find that AHP is one of the earliest methods to deal with MCGDM problems [108]. TOPSIS and VIKOR as two commonly used and well-known comparative methods, which has similar calculation logic [109]. WASPAS is a novel method which has been put forward in recent years, which has higher consistency and accuracy [31]. AHP, TOPSIS, VIKOR, and WASPAS are the popular and classical methods in recent years [110, 111], so we choose these four methods to compare with the proposed methods. Table 13 represents the comparison results.

In the prioritization of alternatives in Table 13, there are differences in the ranking results of various methods when the parameters change. However, most of the prioritization of alternatives prove that A_2 is the best supplier and A_1 is the worst supplier. Among this, the IF-TOPSIS and IF-AHP are consistent with the result of the method proposed in this paper. IF-VIKOR has the same ranking order when parameters change. The value of λ in IF-WASPAS greatly affects the priority. When $\lambda \in [0.1, 0.5]$, the result is consistent with that of this paper. When $\lambda \geq 0.6$, the fourth alternative becomes the best choice. With the increase of the value of λ, the ranking result is constantly changing. It can be concluded that the single WASPAS method is greatly influenced by the value of λ and has weak stability. The content of Table 12 shows that the value of λ has little influence on the prioritization of the proposed method, so it is concluded that hybrid method we proposed can improve the accuracy and stability of ranking results.

Table 10: The positive/negative ideal solution of each criterion.

Criteria	$\widetilde{v}_j^+$	$\widetilde{v}_j^-$
G_1	(1, 0)	(0.779, 0.187)
G_2	(1, 0)	(0.879, 0.099)
G_3	(0.719, 0.208)	(0.401, 0.501)
G_4	(1, 0)	(0.863, 0.117)
G_5	(1, 0)	(0.79, 0.182)
G_6	(0.817, 0.152)	(0.607, 0.316)
S_1	(1, 0)	(0.773, 0.187)
S_2	(1, 0)	(0.845, 0.135)
S_3	(0.903, 0.074)	(0.828, 0.15)
S_4	(0.861, 0.125)	(0.733, 0.224)
O_1	(1, 0)	(0.711, 0.244)
O_2	(0.906, 0.076)	(0.867, 0.113)
O_3	(0.862, 0.106)	(0.772, 0.192)

Table 11: The D_i^+, D_i^-, and CC_i of each alternative.

	A_1	A_2	A_3	A_4
D_i^+	0.168	0.094	0.112	0.133
D_i^-	0.096	0.137	0.109	0.104
CC_i	0.364	0.595	0.492	0.439

$D_1^+ = \sqrt{(1/2m)\sum_{j=1}^{m}[(\mu_j^+ - \mu_{ij})^2 + (v_j^+ - v_{ij})^2 + (\pi_j^+ - \pi_{ij})^2]} = 0.168.$

Table 12: The D_1^+, D_1^-, and CC_i of each alternative by each λ value.

		D_i^+	D_i^-	CC_i	Prioritization of alternatives
$\lambda = 0.1$	A_1	0.281	0.934	0.77	$A_2 > A_3 > A_4 > A_1$
	A_2	0.025	0.953	0.975	
	A_3	0.043	0.939	0.956	
	A_4	0.08	0.931	0.921	
$\lambda = 0.2$	A_1	0.282	0.915	0.764	$A_2 > A_3 > A_4 > A_1$
	A_2	0.034	0.935	0.965	
	A_3	0.054	0.919	0.945	
	A_4	0.088	0.912	0.912	
$\lambda = 0.3$	A_1	0.285	0.068	0.192	$A_2 > A_3 > A_4 > A_1$
	A_2	0.048	0.107	0.692	
	A_3	0.068	0.08	0.54	
	A_4	0.098	0.064	0.397	
$\lambda = 0.4$	A_1	0.138	0.08	0.366	$A_2 > A_3 > A_4 > A_1$
	A_2	0.067	0.12	0.644	
	A_3	0.087	0.091	0.513	
	A_4	0.112	0.081	0.42	
$\lambda = 0.5$	A_1	0.168	0.096	0.364	$A_2 > A_3 > A_4 > A_1$
	A_2	0.094	0.137	0.595	
	A_3	0.112	0.109	0.492	
	A_4	0.133	0.104	0.439	
$\lambda = 0.6$	A_1	0.211	0.117	0.357	$A_2 > A_3 > A_4 > A_1$
	A_2	0.132	0.159	0.546	
	A_3	0.147	0.134	0.477	
	A_4	0.164	0.132	0.447	
$\lambda = 0.7$	A_1	0.364	0.152	0.365	$A_2 > A_3 > A_4 > A_1$
	A_2	0.189	0.189	0.5	
	A_3	0.195	0.172	0.468	
	A_4	0.211	0.168	0.442	
$\lambda = 0.8$	A_1	0.343	0.197	0.365	$A_3 > A_2 > A_4 > A_1$
	A_2	0.271	0.23	0.459	
	A_3	0.262	0.23	0.468	
	A_4	0.285	0.216	0.43	
$\lambda = 0.9$	A_1	0.46	0.399	0.464	$A_2 = A_3 = A_4 > A_1$
	A_2	0.39	0.391	0.5	
	A_3	0.358	0.358	0.5	
	A_4	0.4	0.4	0.5	

Table 13: Comparison of the alternative ranking with the classical MCGDM methods.

Method		Prioritization of alternatives
IF-TOPSIS		$A_2 > A_3 > A_4 > A_1$
IF-WASPAS	$\lambda \in [0.1, 0.5]$	$A_2 > A_3 > A_4 > A_1$
	$\lambda = 0.6$	$A_4 > A_1 > A_2 > A_3$
	$\lambda = 0.7$	$A_4 > A_3 > A_1 > A_2$
	$\lambda \in [0.8, 0.9]$	$A_4 > A_1 > A_3 > A_2$
IF-AHP		$A_2 > A_3 > A_4 > A_1$
IF-VIKOR	$\gamma = 0.3/\gamma = 0.5/\gamma = 0.8$	$A_2 > A_3 > A_1 > A_4$
The proposed method	$\lambda = 0.5\lambda = 0.5$	$A_2 > A_3 > A_4 > A_1$

7.4. Discussion. The purpose of this section is to discuss the advantages of the supplier selection method used in this paper. The method is specifically manifested in the following two aspects:

(1) The ranking results are more accurate. WASPAS method has clear logic and simple calculation process, which makes the decision results more precise. In this paper, TOPSIS is integrated at the end of WASPAS to make the alternatives closer to the positive ideal solution (PIS) and away from the negative ideal solution (NIS). In this way, the results based on WASPAS and TOPSIS are more consistent.

(2) Criteria weighting processes are improved. Compared with the traditional AHP, the BWM calculation process only involves integers, and the calculation steps are greatly reduced, which reduces the arithmetic difficulty for decision makers and improves the consistency of the results.

8. Conclusion

By considering the environmental protection and the globalization of the supply chain, resilient-green supplier selection has become a critical issue in the supply chain management. A supplier selection model integrating WASPAS and TOPSIS method based on intuitionistic fuzzy sets is provided. Firstly, the weights of each criteria are measured by the BWM method; secondly, the decision matrix is processed with the integrated WASPAS and TOPSIS, and the alternatives are ranked.

This paper makes two contributions to the research studies on the resilient-green supplier selection. (1) In the background of supply chain management, most scholars have established the relationship between the resilience and greenness from the perspective of supply chain design, but there are few studies focusing on the resilient-green supplier selection. According to the green manufacturing process, resilient-related characteristics, and their intersection, the resilient-green supplier selection criteria system is constructed. (2) In terms of the research methods, a hybrid decision-making method based on the intuitionistic fuzzy numbers is proposed, integrating the WASPAS and TOPSIS to reduce the uncertainty and inaccuracy in the decision-making process. The intuitionistic fuzzy number reflects the preferences of the decision makers more accurately and avoid the fuzziness. In addition, the decision-making system proposed can not only solve the supplier selection problem but also address the site selection, supplier segmentation, performance evaluation, and other issues.

This paper proves the validity of the decision-making model through the illustrative examples, but there are still some limitations. Firstly, the determination of criteria weight by experts was dealt with. Future research studies should mention the method of weighting experts. Secondly, the intuitionistic fuzzy numbers are only used in the ranking stage. Introduction of the fuzzy sets into the weight determination is an important work. Finally, this paper proposes a decision-making method suitable for the intuitionistic fuzzy numbers. And future research studies should be extended to the application of other fuzzy sets.

Data Availability

All related data are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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