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A Structured Fuzzy Framework for Risk Prioritization in Sustainable Food Supply Chains: Supporting the Sustainable Development Goals (SDGs) through a Case Study in Indonesia

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ABSTRACT

Effective risk assessment is vital for achieving the Sustainable Development Goals (SDGs), particularly in food supply chains where uncertainty and complexity are prevalent. This study proposes a structured fuzzy framework that combines the Fuzzy Delphi Method and Fuzzy Best Worst Method (Fuzzy BWM) to identify, evaluate, and prioritize sustainability-related risks. A case study conducted in Indonesia involved expert insights from various sectors within the food supply chain. The Fuzzy Delphi Method was used to screen and validate relevant risks, while Fuzzy BWM enabled the prioritization of these risks across economic, social, and environmental dimensions. The results reveal that economic-related risks are of primary concern, followed by critical risks in the social and environmental domains. This framework improves decision-making accuracy by managing uncertainty and providing a clear basis for prioritizing actions. The findings offer practical guidance for companies seeking to strengthen their sustainability strategies and contribute meaningfully to SDGs through more resilient and responsible supply chain managemen.

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1. INTRODUCTION

Sustainable supply chains play a strategic role in enhancing business continuity by integrating environmental, social, and economic principles into core operations. This integration not only creates added value for stakeholders but also supports long-term corporate sustainability through reduced environmental impact, improved energy efficiency, and optimized waste management practices [1–5]. These efforts further enhance corporate reputation, promote innovation, and increase profitability [6–10]. Financial instruments such as green bonds and sustainability-linked loans help strengthen funding mechanisms for sustainability initiatives by fostering transparency and accountability across the supply chain [11, 12]. Additionally, the adoption of Green Supply Chain Management practices contributes to improved economic performance and reduced greenhouse gas emissions, offering firms a competitive advantage in the global market [13]. As a result, sustainable supply chains support organizational objectives while contributing meaningfully to global sustainability goals [14–16].

Despite these advantages, Sustainable Supply Chain (SSC) management continues to face significant challenges due to supply and cost volatility. These uncertainties can disrupt the flow of materials, information, and capital, ultimately leading to increased operational costs and reduced sales performance [17, 18]. Overcoming such challenges requires not only the adoption of innovative technologies but also the implementation of long-term sustainability principles encompassing economic, social, and environmental dimensions. The need to restructure incentive systems to align stakeholder objectives has been emphasized [19], while the strategic benefits of SSC—ranging from environmental stewardship to social responsibility and competitiveness—have been widely acknowledged [20]. In this context, effective risk assessment emerges as a critical component in ensuring operational efficiency, economic resilience, and the realization of sustainable outcomes.

Nevertheless, risk assessment in SSC contexts often faces the persistent challenge of uncertainty, particularly in evaluating the relevance and priority of risks related to sustainability [21, 22]. Traditional models that rely on crisp data frequently fail to capture the ambiguity present in expert judgment, leading to inaccuracies in evaluating risk impacts [23]. To address this issue, a fuzzy-based approach is needed; one that can manage uncertainty while producing structured, measurable results. Without such an approach, decision-makers may overlook highly critical risks, thereby hindering progress toward sustainability objectives. Incomplete or imprecise risk assessments can jeopardize the triple bottom line (economic viability, social equity, and environmental sustainability), ultimately weakening a firm's competitiveness in global markets [24, 25]. Therefore, it is imperative to develop a robust risk assessment framework capable of handling fuzzy data in both relevance evaluation and prioritization [26–28].

Various techniques have been developed to support risk assessment in supply chains. These include traditional multicriteria decision-making methods such as the Analytic Hierarchy Process (AHP) [29], the Analytic Network Process (ANP) combined with the House of Risk (HOR) framework [30, 31], and the Failure Mode and Effects Analysis (FMEA) [32]. Although effective in producing structured outputs, these methods often depend on crisp inputs and are limited in their ability to manage real-world uncertainty. In response to these limitations, more recent studies have introduced fuzzy logic-based approaches such as Fuzzy AHP [33] and Fuzzy Inference Systems (FIS) [34], which are more suitable for modeling ambiguous and subjective expert inputs. These approaches have gained traction, particularly in agro-industrial and food supply chains, where sustainability-related risks are more

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pronounced. Examples include the application of the Delphi method to food sector risk analysis [35], the use of AHP in agro-industrial risk evaluation [29], and the development of fuzzy-based models to address uncertainty in prioritizing risks [36]. Despite these contributions, most of the existing models lack integration between risk relevance, sustainability dimensions, and prioritization mechanisms.

A clear gap persists in the literature regarding comprehensive risk assessment frameworks that holistically integrate relevance evaluation and prioritization within a sustainability context. The majority of previous research has either focused on risk identification or prioritization in isolation, without explicitly linking the analysis to sustainable development objectives. Even in studies that attempt to incorporate sustainability, relevance filtering is often absent or insufficiently structured, and uncertainty in expert judgment is rarely accounted for. Consequently, these limitations reduce the strategic applicability of their findings and hinder their implementation in complex supply chain environments.

To bridge this gap, the present study proposed an integrated risk assessment framework that combines the Fuzzy Delphi Method for evaluating the relevance of risks and the Fuzzy Best Worst Method (Fuzzy BWM) for prioritization. The proposed model enables the filtering and ranking of risks based on expert consensus, using fuzzy logic to handle imprecision in judgments and enhance result reliability. The research specifically targets the food sector, where supply chains are highly susceptible to disruption and sustainability challenges are particularly critical. Through this integrated framework, the study contributes both theoretically and practically by enabling more accurate, consistent, and actionable risk assessments that support improved strategic planning, operational stability, and long-term supply chain sustainability.

In alignment with the global agenda, sustainable supply chains also contribute directly to the realization of several Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). By identifying and prioritizing risks that impact food security, social equity, and environmental performance, this study promotes the development of risk mitigation strategies that are operationally effective and sustainability-driven. Many existing frameworks fail to establish a direct link between risk prioritization and SDG targets. Therefore, the fuzzy-based framework presented in this study addresses that gap by equipping organizations with tools to simultaneously improve supply chain resilience and strengthen their contribution to global sustainability commitments.

2. LITERATURE REVIEW

The importance of risk assessment in sustainable supply chains has driven scholars to explore systematic methods for identifying and prioritizing relevant risks. This literature review builds a theoretical foundation by evaluating the strengths and limitations of existing approaches. Key findings are synthesized in **Table 1**, serving as a reference for the development of the proposed framework.

Several studies have addressed risk relevance in supply chains, though with varying approaches and scope. One study used the Delphi method with crisp data to evaluate risk relevance based on expert opinion, effectively filtering important risks but without incorporating sustainability dimensions or conducting further prioritization, thus limiting its managerial utility [35]. Another study combined Gray Delphi, DEMATEL, and ANP to assess both relevance and sustainability but still relied on crisp data, which is less capable of handling the uncertainty in expert preferences [37].

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Other research has focused solely on risk assessment without integrating relevance or sustainability. For example, several studies applied ANP-House of Risk (HOR), AHP, and FMEA using crisp data to identify and evaluate risks within operational contexts [29–32]. While these methods offer structured and measurable outcomes, they do not address whether the identified risks are relevant to sustainability or future strategic goals. Some researchers have introduced fuzzy data approaches, such as Fuzzy AHP and Fuzzy Inference Systems, to manage uncertainty in decision-making, but these models also overlook the relevance aspect of risk [33, 34].

Research that emphasizes risk assessment within sustainability contexts has contributed to understanding how risks affect the economic, social, and environmental dimensions of supply chains. One study applied an aggregate metric based on crisp data to assess sustainability risks in the automotive and apparel sectors, highlighting the importance of sustainable risk management while still neglecting uncertainty in expert preferences [38]. Another study employed Fuzzy AHP to evaluate sustainability risks in the manufacturing sector, providing more modeling flexibility but not including risk relevance filtering or a systematic prioritization framework [39].

The literature reveals a clear gap: most studies address either risk identification or risk prioritization without fully integrating sustainability or considering the relevance of each risk. Although a few studies have begun incorporating sustainability dimensions into risk evaluation, they generally lack structured methods for pre-screening irrelevant risks. In addition, the continued reliance on crisp data limits the capacity of these models to reflect the ambiguity and subjectivity present in expert evaluations.

This research addresses the gap by proposing an integrated framework that combines Fuzzy Delphi for risk relevance assessment and Fuzzy Best Worst Method (Fuzzy BWM) for risk prioritization. The framework focuses on filtering and evaluating risks based on their significance to supply chain sustainability, using fuzzy logic to manage uncertainty in expert judgment. This approach allows for a more accurate and structured prioritization of risks across economic, social, and environmental dimensions, ultimately supporting strategic decision-making aligned with sustainability goals.

Table 1. Literature review of supply chain risk assessment research.

Risk Assessment	Relevance of Risk	Sustainable	Method	Data	Sector	Reference
√	-	-	ANP-House of Risk (HOR)	Crisp	Agro-industry	[30]
√	-	-	HOR	Crisp	Agroindustry	[31]
-	√	-	Delphi	Crisp	Food	[35]
√	-	-	AH	Crisp	Agroindustry	[29]
√	-	-	Fuzzy shape	Fuzzy	Agro-industry	[36]
√	-	-	FMEA	Crisp	Automotive	[32]
√	-	-	Fuzzy Inference System (FIS)	Fuzzy	Manufacturing	[40]
√	-	-	AHP	Crisp	Telecommunication equipment	[41]

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Table 1 (continue). Literature review of supply chain risk assessment research.

Risk Assessment	Relevance of Risk	Sustainable	Method	Data	Sector	Reference
√	-	-	AHP-DEMATEL	Crisp	-	[42]
√	-	-	Fuzzy AHP	Fuzzy	Halal food	[33]
√	-	√	Fuzzy AHP	Fuzzy	Manufacturing	[39]
√	-	-	AHP	Crisp	Manufacturing	[43]
√	-	√	Aggregate metric	Crisp	Automotive and apparel	[38]
√	√	√	Gray Delphi-DEMATEL-ANP	Crisp	Lithium-ion battery	[37]
√	-	-	QFD	Crisp	Transportation	[44]
√	-	-	Fuzzy Inference System (FIS)	Fuzzy	-	[34]
√	√	√	Fuzzy Delphi, Fuzzy BWM	Fuzzy	Food	This research

3. METHODS

This study adopts a structured multi-phase methodology that integrates the Fuzzy Delphi Method and Fuzzy Best Worst Method (Fuzzy BWM) to identify, assess, and prioritize sustainability-related risks in food supply chains. The methodological framework is designed to manage uncertainty in expert judgments and to support strategic decision-making aligned with sustainable development objectives. The framework consists of three main stages: risk identification, risk relevance assessment using Fuzzy Delphi, and risk prioritization using Fuzzy BWM.

3.1. Risk Identification

The initial stage involved identifying potential risks in sustainable food supply chains by combining a comprehensive literature review and expert consultation. Relevant academic journals, case studies, and technical reports were reviewed to gather common risk elements associated with economic, social, and environmental dimensions. In addition, a focus group discussion (FGD) was conducted with ten experts from academia, industry, and supply chain management to validate and refine the risk register. The identified risks were categorized according to the main supply chain functions (Plan, Source, Make, and Deliver) to ensure a comprehensive mapping across all operational areas.

3.2. Risk Relevance Assessment using Fuzzy Delphi Method

The second stage applied the Fuzzy Delphi Method to evaluate the relevance of each identified risk based on expert consensus. A structured questionnaire was distributed to the same group of ten experts. Respondents assessed each risk using linguistic variables (Low, Medium, High, Very High), which were then converted into Triangular Fuzzy Numbers (TFNs) to account for uncertainty and subjectivity. The aggregation of expert judgments was performed using the Center of Gravity (COG) defuzzification method to obtain crisp scores for each risk. Risks with a relevance score below a pre-determined threshold were eliminated from further analysis. This process ensured that only the most significant and contextually relevant risks were prioritized in the subsequent phase.

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3.3. Risk Prioritization using Fuzzy Best Worst Method (Fuzzy BWM)

In the third stage, the Fuzzy BWM was employed to determine the priority weights of the remaining risks. Experts were asked to identify the most critical (best) and least critical (worst) risk elements in each sustainability dimension. Pairwise fuzzy comparisons were then made between the best risk and all others, and between all risks and the worst one. These comparisons were used to formulate a fuzzy optimization model to calculate the local weights of each risk. The defuzzified results yielded crisp weights, which were normalized to derive global priorities across all sustainability dimensions. The consistency ratio was also calculated to validate the reliability of expert judgments.

3.4. Case Study Design

The proposed methodology was applied in a case study of the food industry in Malang, Indonesia. The selection of this location was based on its relevance as a regional food production hub, where sustainability challenges are prominent. Ten experts with extensive experience in food supply chains, sustainability, and risk management participated in all stages of the analysis. Their diverse backgrounds ensured a holistic evaluation of risk factors and enhanced the contextual validity of the results.

4. RESULTS AND DISCUSSION

4.1. Proposed SSC Management Framework

From the literature discussion that has identified various methods in sustainable supply chain risk management, this research proposes a structured framework using Fuzzy Delphi and BWM approaches to ensure a more accurate and relevant analysis of the company's needs, based on **Figure 1**. The figure shows that the proposed framework for sustainable supply chain risk assessment consists of three main stages. The first stage is the identification of risks in the sustainable supply chain. In the second stage, risk relevance assessment is conducted by experts using the Fuzzy Delphi method to filter risks based on relevance value, where risks with a value of less than 0.5 are eliminated. The relevant risks were further analyzed using the Fuzzy BWM method in stage three. Experts systematically determine the best and worst risks to calculate risk weights at this stage. This process results in risk prioritization that can be used as a basis for more effective and strategic risk management. Details of each stage are presented in the following sub-sections.

4.2. SSC Risk Identification Stage

The risk identification stage in sustainable supply chains was conducted systematically to ensure that all relevant risk elements were accurately captured. The process began with a comprehensive literature review aimed at extracting risks previously identified in studies related to the food sector and sustainable supply chains. This review encompassed peer-reviewed journals, academic articles, and technical reports, allowing for the consolidation of existing knowledge and the identification of commonly cited risk factors.

To complement and validate the findings from the literature, a focus group discussion (FGD) was organized involving experts in supply chain management, sustainability, and risk analysis. These experts contributed insights based on their professional experience, ensuring that the identified risks were contextually appropriate and reflected operational realities in the field. The FGD also served to confirm the completeness of the risk register and to align it with the practical challenges faced by organizations operating in the food supply chain sector [45, 46].

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The combination of insights from the literature and expert discussion resulted in the development of an initial risk register, which formed the basis for the subsequent risk relevance assessment using the Fuzzy Delphi Method [47]. This dual-sourced approach provides a structured and transparent foundation for risk identification, enhancing the validity and replicability of the framework across various industrial contexts.

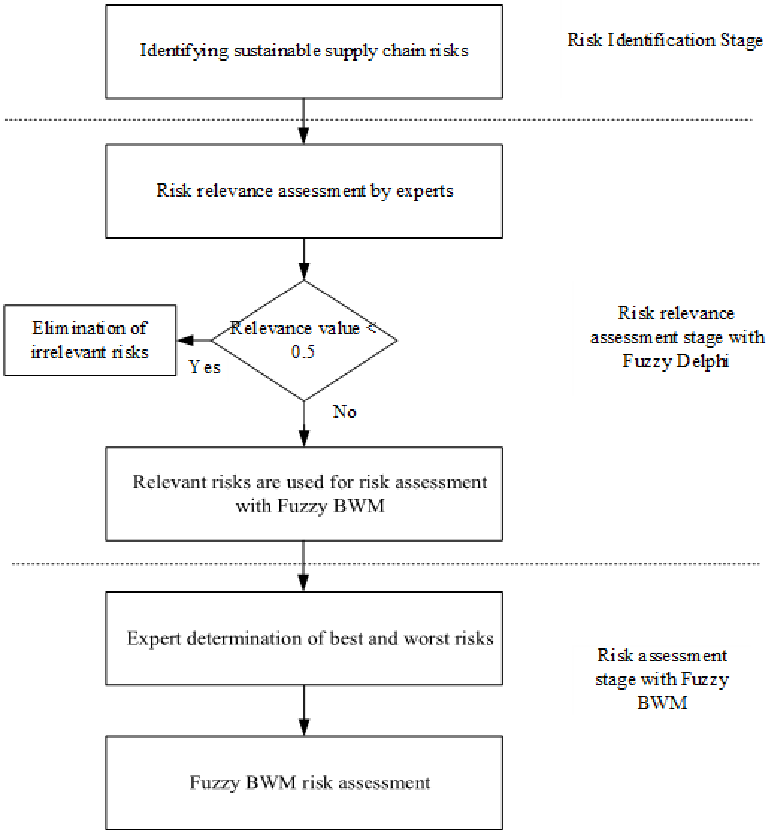

Figure 1. Proposed SSC risk assessment framework.

4.3. Risk Relevance Assessment Stage with Fuzzy Delphi

The risk relevance assessment stage was conducted using the Fuzzy Delphi Method, beginning with the distribution of structured questionnaires to a panel of experts with extensive experience in supply chain operations and sustainability. These experts were selected based on their domain knowledge and practical involvement in managing risks within food supply chains. The primary objective of the questionnaire was to evaluate how relevant each identified risk was to real-world operational conditions encountered by companies in the sector [48].

To accommodate the inherent uncertainty and subjectivity in expert judgments, the questionnaire incorporated linguistic variables translated into fuzzy numerical values. Experts were asked to assess each risk based on a four-point fuzzy scale, which included the categories: Low (R), Medium (S), High (T), and Very High (ST). These linguistic terms were converted into triangular fuzzy numbers to enable further quantitative analysis using fuzzy logic principles. The definitions and corresponding fuzzy values used in the questionnaire are presented in **Table 2**.

Each linguistic variable is represented as Triangular Fuzzy Numbers (TFN) to capture the uncertainty in expert judgment. This fuzzy assessment is then processed to convert fuzzy

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numbers into crisp numbers using the Center of Gravity (COG) method. The risk relevance value is calculated using Equation (1).

Table 2. Delphi Fuzzy linguistic variables.

Linguistic Variables	Code	TFN
Low	R	0.0, 0.2, 0.4
Medium	S	0.2, 0.4, 0.6
High	T	0.4, 0.6, 0.8
Very High	ST	0.6, 0.8, 1.0

$$S_j = \frac{a_j+b_j+c_j}{3} \tag{1}$$

where, a_j is the minimum value of the fuzzy number for the j-th risk, representing the lower bound given by the experts, denoted by $a_j = Min_i\{a_{ij}\}$. b_j is the average fuzzy middle value obtained by summing the fuzzy middle values of all experts for the j th risk and dividing it by the number of experts modeled by $b_j = \frac{1}{n}\sum_{i=1}^{n} b_{ij}$. Meanwhile, c_j is the maximum value of the fuzzy number for the j-th risk, representing the upper bound of the expert judgment formulated with $c_j = Max_i\{c_{ij}\}$.

Risks with a relevance value (S_j) of less than 0.5 are eliminated from further analysis as they are considered irrelevant. This elimination process ensures that only relevant and significant risks to the company's operational context proceed to the next stage. After the elimination stage, risks that meet the relevance criteria are used as input for the priority assessment stage using the Fuzzy BWM method. This approach ensures that each analyzed risk is highly relevant to the company's operational context, supporting more effective and efficient strategic decisions. This procedure allows the risk relevance assessment process to be replicated across different industry contexts easily.

4.4. Risk Assessment Stage with Fuzzy BWM

The risk assessment in this study uses the Fuzzy BWM method developed by Guo and Zhao [52]. This method consists of systematic steps to determine the priority weight of risks in a sustainable supply chain context. The first step is the identification of risk alternatives$(C_1, C_2, \dots \dots C_n)$, which are relevant to the sustainable supply chain system. These risk alternatives are obtained through a literature review and in-depth discussions with experts to ensure their suitability for the operational conditions of the system.

After the risk register is compiled, the best risk(C_B) and the worst risk(C_W) are determined based on expert judgment. The best risk is the factor that has the most significant impact on the system's sustainability. In contrast, the worst risk is the factor with the least impact. The determination of these risks is done through an assessment based on the experience and knowledge of the decision-makers.

The next step is to perform a fuzzy preference comparison between the best risk(C_B) and the other risks, represented by the fuzzy vector $A_B = \tilde{a}_{B1}, \tilde{a}_{B2}, \dots, \tilde{a}_{Bn}$, as presented in Equation (2). On the other hand, the fuzzy preference of the other risk against the worst risk (C_W) is represented by the fuzzy vector $A_W = \tilde{a}_{1W}, \tilde{a}_{2W}, \dots, \tilde{a}_{nW}$, as listed in Equation (3). In this comparison, the fuzzy values of the best risk to itself $(\tilde{a}_{\mathrm{BB}})$ and the worst risk to itself $(\tilde{a}_{\mathrm{WW}})$ are set equal to (1,1,1).

The next step is to perform a fuzzy preference comparison for the best risk (C_B) and the worst risk(C_W). In this process, a fuzzy pairwise comparison is performed. The fuzzy preference of the best risk against the other risks is represented by the fuzzy vector Equation

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(2). On the other hand, the fuzzy preference of the other risk over the worst risk is represented by the fuzzy vector Equation (3).

$$A_B = \tilde{a}_{B1}, \tilde{a}_{B2}, \dots, \tilde{a}_{Bn} \quad (2)$$

$$A_W = \tilde{a}_{1W}, \tilde{a}_{2W}, \dots, \tilde{a}_{nW} \quad (3)$$

The following process is to calculate the optimal weight of each risk by minimizing the maximum deviation value ($\tilde{\xi}^*$) between the fuzzy preferences given by the decision maker and the calculated fuzzy weights. This optimization model is formulated in Equation (4), which ensures that the resulting fuzzy weights are consistent with the expert's preferences. In this model, the fuzzy weight of the best risk is expressed asl_B^W, m_B^W, u_B^W , the worst risk as(l_W^W, m_W^W, u_W^W) , and the other risks as $((l_j^W, m_j^W, u_j^W)$. The optimization result provides a fuzzy weight value for each risk represented as $(\widetilde{W}_1^*, \widetilde{W}_2^*, \dots \dots \widetilde{W}_n^*)$.

The crisp values of the fuzzy weights are calculated using the *defuzzification* method expressed in Equation (5). This process results in the final weight $R\left(\widetilde{W}_i^*\right)$.

These weights are then used to determine the priority ranking of risks in the system. The final step is to evaluate the consistency of the results by calculating the consistency ratio (CR) using Equation (6). The consistency ratio ensures that the fuzzy preferences given by the experts match the calculated fuzzy weights. The consistency index is tested against certain limits, such as the upper bound of fuzzy values (7/2, 4, 9/2). If the CR value is low, the results are considered valid and can be used for decision-making [53]. The Triangular Fuzzy Numbers (TFN) scale and the BWM fuzzy consistency index is shown in **Table 3**.

$$\min \tilde{\xi}^* \; s.t \begin{cases} \left| \frac{(l_B^W, m_B^W, u_B^W)}{(l_j^W, m_j^W, u_j^W)} - (l_{Bj}, m_{Bj}, u_{Bj}) \right| \leq (k^*, k^*, k^*) \\ \left| \frac{(l_j^W, m_j^W, u_j^W)}{(l_W^W, m_W^W, u_W^W)} - (l_{jW}, m_{jW}, u_{jW}) \right| \leq (k^*, k^*, k^*) \\ \sum_{j=1}^{n} R\left(\widetilde{W}\mathrm{j}\right) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ l_j^w \geq 0 \\ j = 1, 2, \dots., n \end{cases} \quad (4)$$

$$R\left(\widetilde{W}_i^*\right) = \frac{(l_i^* + 4m_i^* + u_i^*)}{6} \quad (5)$$

$$(\tilde{a}_{Bj}, -\tilde{\xi}) \times (\tilde{a}_{jW}, -\tilde{\xi}) = (\tilde{a}_{BW} + \tilde{\xi}) \quad (6)$$

Table 3. Triangular Fuzzy Numbers (TFN) and consistency of fuzzy indices.

Linguistic term	Equally Important (EI)	Weakly Important (WI)	Fairly Important (FI)	Very Important (VI)	Extremely Important (EX)
ãBW	(1,1,1)	(2/3,1, 3/2)	(3/2, 2,5/2)	(5/2,3,7/2)	(7/2,4,9/2)
CI	3.00	3.80	5.29	6.69	8.04

4.5. Data and Case Study

This research utilizes data from a case study of the food industry in Malang, Indonesia. The study was designed to evaluate risks in sustainable supply chains by engaging 10 experts with deep expertise in food industry operations, risk management, and sustainability. The experts came from various fields, including academia, industry practitioners, and supply chain managers, to ensure comprehensive coverage and relevance of the data generated.

The initial stage of risk identification was conducted by combining the approaches of a comprehensive literature review and focus group discussions (FGDs) with experts. The

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literature aimed to identify elements of risk that often arise in the context of sustainable supply chains, particularly in the food sector. The literature reviewed included relevant journal articles, research reports, and case studies. The results of this review provided an initial list of risk elements that were then discussed in FGDs with experts. These discussions verified the relevance of the identified risks. They complemented the risk register by including specific risks relevant to Malang's food industry context. This combination of approaches ensured that the resulting risk elements reflected operational complexities and real sustainability challenges.

The research data included the identification of various risk elements based on the three dimensions of sustainability, namely economic (EC), social (S), and environmental (E). The risks identified through the literature review and discussions with experts are summarized in detail in **Table 4**. Each risk element is further classified based on the activities in the supply chain, i.e., plan, source, make, and deliver, as well as the associated sustainability dimensions. This classification provides a systematic framework for understanding the risks at each supply chain process stage.

The relevance of each risk element was assessed using the Fuzzy Delphi method, the results of which are presented in **Table 5**. This assessment involved expert evaluation to determine the level of relevance of each risk to the system's sustainability. Risks with high relevance proceeded to the subsequent analysis stage using the Fuzzy BWM method.

The best and worst risk assessment is conducted for each risk dimension at the risk analysis stage. **Table 6** presents the results of the overall best and worst risk assessments by risk dimension. Furthermore, a more detailed analysis was conducted on each sustainability dimension. **Table 7** presents the results of the best and worst risk assessments for the economic dimension, **Table 8** for the social dimension, and Table 9 for the environmental dimension. This assessment aims to determine priority risk elements that require special attention in sustainable supply chain management.

Table 4. Risk identification.

Dimensions of Sustainability	**Supply Chain Activity**	**Risk Elements**
Economics (EC)	Plan (P1)	An increase in the inflation rate increases operating costs. (ECP 1) Inability to forecast demand correctly. (ECP 2)
	Source (S1)	Delay in the arrival of raw materials. (ECS 1) Poor quality of raw materials. (ECS 2) Fluctuations in the price of materials used. (ECS 3)
	Make (M1)	There is product damage or defects in the packaging while in storage. (ECM 1) Risk of production disruption, such as equipment breakdown, that may disrupt production. (ECM 2)
	Deliver (D1)	Product damage or packaging defects occur during transportation. (ECD 1) The risk of losing goods in transit can result in losses. (ECD 2)

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Table 4 (continue). Risk identification.

Dimensions of Sustainability	Supply Chain Activity	Risk Elements
Social (S)	Plan (P2)	The quality of the workers' human resources, namely their non-compliance in carrying out their duties following the SOP. (SP 1)
		Interference with community relations, as the community may influence the operational license. (SP 2)
	Source (S2)	Failure in supplier selection. (SS 1)
		The fulfillment of workers' rights is essential because the non-fulfillment of workers' rights in the supply chain can lead to labor dissatisfaction and conflict. (SS 2)
	Make (M2)	Lack of competent labor for production. (SM 1)
		Risk of using packaging materials that are not hygienic and sterile. (SM 2)
	Deliver (D2)	Product deliveries made at night disturb the surrounding community. (SD 1)
		Unsafe deliveries can harm customers and the company's reputation. (SD 2)
Environment (E)	Plan (P3)	The company's policy is to purchase environmentally friendly products and raw materials; a risk arises if the supply meets these criteria is limited. (EP 1)
		Climate change can affect the stability of raw material supply. (EP 2)
	Source (S3)	Overusing water in production can disrupt water availability, result in groundwater depletion, and damage the water environment. (ES 1)
		Water or air pollution from supplier operations may create environmental problems. (ES 2)
	Make (M3)	Lack of adequate waste disposal facilities. (EM 1)
		The absence of plastic waste reduction in production can increase environmental problems. (EM 2)
	Deliver (D3)	Increased carbon emissions during transportation can contribute to climate change. (ED 1)
		The use of unsustainable packaging materials can create waste and environmental problems. (ED 2)

Table 5. Risk relevance assessment.

Code	Expert									
	1	2	3	4	5	6	7	8	9	10
ECP 1	ST	ST	T	ST	ST	T	ST	ST	ST	ST
ECP 2	S	S	ST	S	S	T	S	S	S	S
ECS 1	T	ST	T	T	ST	T	T	T	ST	T
ECS 2	T	S	S	S	S	S	ST	S	S	S
ECS 3	T	ST	T	T	T	ST	T	T	T	T

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Table 5 (continue). Risk relevance assessment.

Code	**Expert**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
ECM 1	R	R	S	R	R	R	R	R	R	R
ECM 2	ST	ST	ST	T	ST	ST	ST	ST	ST	ST
ECD 1	R	S	S	R	S	S	T	S	S	S
ECD 2	ST	ST	ST	ST	T	ST	ST	ST	ST	ST
SP 1	R	R	S	S	S	R	S	R	S	S
SP 2	R	R	R	S	S	R	R	R	R	R
SS 1	ST	T	S	T	T	ST	ST	T	T	T
SS 2	ST	ST	ST	ST	T	T	ST	T	ST	ST
SM 1	ST	T	T	T	T	S	ST	T	T	T
SM 2	S	T	T	T	T	ST	T	T	T	ST
SD 1	R	R	S	R	S	R	R	R	R	R
SD 2	ST	ST	ST	ST	ST	ST	ST	T	ST	ST
EP 1	T	T	T	T	T	ST	ST	T	T	T
EP 2	ST	ST	T	ST	ST	ST	ST	ST	ST	ST
ES 1	S	T	T	T	T	ST	ST	T	T	T
ES 2	S	R	R	S	S	S	R	S	S	S
EM 1	T	ST	ST	ST	ST	ST	ST	ST	ST	ST
EM 2	T	S	ST	T	T	T	T	T	T	T
ED 1	S	T	S	S	S	R	S	S	T	S
ED 2	ST	T	S	T	T	ST	ST	T	T	T

Table 6. Best and worst risk assessment based on risk dimension.

Best Risk : EC	**Linguistic Assessment**	**TFN Value**
EC	EI	(1,1,1)
S	WI	(2/3,1,3/2)
E	VI	(5/2,3,3/5)
Worst Risk: E	**Linguistic Assessment**	**TFN Value**
EC	VI	(5/2,3,3/5)
S	WI	(2/3,1,3/2)
E	EI	(1,1,1)

Table 7. Best and worst risk assessment based on economic risk dimension.

Best Risk: ECM 2	**Linguistic Assessment**	**TFN Value**
ECP 1	VI	(5/2,3,7/2)
ECP 2	EX	(7/2,4,9/2)
ECS 1	FI	(3/2,2,5/2)
ECS 3	FI	(3/2,2,5/2)
ECM 2	EI	(1,1,1)
ECD 2	WI	(2/3,1, 3/2)
Worst Risk: ECP 2	**Linguistic Assessment**	**TFN Value**
ECP 1	VI	(5/2,3,7/2)
ECP 2	EI	(1,1,1)
ECS 1	FI	(3/2,2,5/2)
ECS 3	FI	(3/2,2,5/2)
ECM 2	EX	(7/2,4,9/2)
ECD 2	WI	(2/3,1, 3/2)

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Table 8. Best and worst risk assessment based on social dimension risk.

Best Risk: SD 2	Linguistic Assessment	TFN Value
SS 1	EX	(7/2,4,9/2)
SS 2	WI	(2/3,1, 3/2)
SM 1	FI	(3/2, 2,5/2)
SM 2	VI	(5/2,3,7/2)
SD 2	EI	(1,1,1)
Worst Risk: SS 2	**Linguistic Assessment**	**TFN Value**
SS 1	EI	(1,1,1)
SS 2	WI	(2/3,1, 3/2)
SM 1	FI	(3/2, 2,5/2)
SM 2	VI	(5/2,3,7/2)
SD 2	EX	(7/2,4,9/2)

Table 9. Best and worst risk assessment based on risk dimension environment.

Best Risk: EP 2	Linguistic Assessment	TFN Value
EP 1	FI	(3/2, 2,5/2)
EP 2	EI	(1,1,1)
ES 1	FI	(3/2, 2,5/2)
EM 1	WI	(2/3,1, 3/2)
EM 2	VI	(5/2,3,7/2)
ED 2	EX	(7/2,4,9/2)
Worst Risk: ED 2	**Linguistic Assessment**	**TFN Value**
EP 1	FI	(3/2, 2,5/2)
EP 2	EX	(7/2,4,9/2)
ES 1	FI	(3/2, 2,5/2)
EM 1	WI	(2/3,1, 3/2)
EM 2	VI	(5/2,3,7/2)
ED 2	EI	(1,1,1)

4.6. Risk Relevance Assessment Results with Fuzzy Delphi

This research found that using the Center of Gravity (COG) method in converting fuzzy numbers to crisp numbers clarifies assessing risk relevance for each identified criterion. The results of the risk relevance calculation (S_j) show that not all risk elements have sufficient value to be considered significant in supply chain sustainability. **Table 10** presents the full results of the S_j values for each risk element based on the economic, social, and environmental dimensions.

In the economic dimension, risks with relevance values below the threshold of 0.5 were eliminated because they were considered irrelevant for further analysis. The three risk sub-criteria eliminated were poor quality of raw materials (ECS 2, S_j =0.49), product damage or defects in packaging while in storage (ECM 1, S_j =0.27), and product damage or defects in packaging during transportation (ECD 1, S_j =0.33S). Other risk elements in the economic dimension, such as raw material delays (ECS 1,S_j =0.69) and raw material price fluctuations (ECS 3, S_j =0.68), were continued to the subsequent analysis stage because they had high relevance values.

In the social dimension, the eliminated risks include workers' non-compliance with SOPs (SP 1, S_j =0.31), disruption of relations with the community that may affect operational licenses (SP 2, S_j =0.28), and product delivery at night that disturbs the surrounding

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community (SD 1, S_j =0.32). Other social risks, such as failure in supplier selection (SS 1,S_j =0.57) and fulfillment of workers' rights (SS 2, S_j =0.71), have high relevance scores, and are considered for further analysis.

In the environmental dimension, the sub-criteria risk of water or air pollution from supplier operations (ES 2, S_j =0.31) and increased carbon emissions during transportation (ED 1, S_j =0.41) were eliminated due to their low relevance values. In contrast, risks such as climate change affecting the stability of raw material supply (EP 2, S_j =0.73) and lack of adequate waste disposal facilities (EM 1, S_j =0.73) showed high relevance and proceeded to the priority assessment stage.

Table 10. Assessment results risk relevance.

Criteria	Risk	Sj Value
Economic	ECP 1	0.72
	ECP 2	0.55
	ECS 1	0.69
	ECS 2	0.49
	ECS 3	0.68
	ECM 1	0.27
	ECM 2	0.73
	ECD 1	0.33
	ECD 2	0.73
Social	SP 1	0.31
	SP 2	0.28
	SS 1	0.57
	SS 2	0.71
	SM 1	0.61
	SM 2	0.61
	SD 1	0.32
	SD 2	0.73
Environment	EP 1	0.68
	EP 2	0.73
	ES 1	0.61
	ES 2	0.31
	EM 1	0.73
	EM 2	0.60
	ED 1	0.41
	ED 2	0.57

From an economic perspective, certain risks were deemed irrelevant in the context of sustainable supply chains. These include poor raw material quality (ECS 2), product damage or packaging defects during storage (ECM 1), and during transportation (ECD 1). Their limited impact on overall operational efficiency and sustainability is attributed to the effective implementation of mitigation systems, such as strict supplier supervision, modern storage technologies, and the use of reliable transportation modes [49]. Furthermore, the financial implications of these risks are relatively minor compared to more significant threats that can disrupt supply chain continuity, such as global distribution disruptions, raw material price volatility, or changes in environmental regulations [50]. Therefore, this study focuses on more strategic risks that pose long-term threats to the economic sustainability of the supply chain.

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Within the social dimension, several risks were also considered to have low relevance. These include non-compliance with standard operating procedures (SP 1), disruption of community relations affecting operating licenses (SP 2), and nighttime deliveries that disturb surrounding communities (SD 1). These risks are considered manageable due to existing organizational mechanisms, including continuous training programs to improve SOP compliance and community engagement initiatives to maintain positive relations [56]. Moreover, the impact of these risks on the long-term sustainability of the supply chain is limited, as they can typically be resolved through short-term interventions that do not compromise the overall system [51].

In terms of environmental risks, elements such as water or air pollution from supplier operations (ES 2) and increased carbon emissions from transportation activities (ED 1) were also considered less relevant. This is largely because their impact is relatively minimal or already well managed through corporate environmental commitments. Many firms have adopted international standards such as ISO 14001 or implemented green supply chain practices. Additionally, transportation-related emissions are often mitigated through route optimization and the adoption of low-emission technologies [52]. As a result, environmental risk assessments tend to focus more on strategic issues, such as regulatory shifts, resource scarcity, or environmental disasters that directly affect supply chain continuity [53].

The results of this study demonstrate that the Fuzzy Delphi Method, when combined with the Center of Gravity (COG) technique, is effective in identifying and filtering risk elements based on their relevance to supply chain sustainability. By applying a relevance threshold of 0.5, only risks deemed significant are advanced to subsequent stages of analysis. This finding is consistent with previous research, which emphasized that fuzzy-based approaches enhance decision-making by addressing uncertainty in expert evaluations [48]. However, this study expands upon prior work by integrating relevance filtering and sustainability dimensions (economic, social, and environmental) specifically within the food supply chain context, offering a contribution that has yet to be fully explored in earlier studies.

A key advantage of this approach lies in its ability to distinguish specific risks within each sustainability dimension. In the economic domain, risks such as raw material delays (ECS 1) and raw material price fluctuations (ECS 3) were identified as the most critical. These findings corroborate existing literature, which emphasizes that such risks are among the primary threats to supply chain efficiency [49]. What distinguishes this study is its incorporation of sustainability criteria, resulting in more comprehensive and contextually relevant assessments.

In the social domain, risks related to the fulfillment of workers' rights (SS 2) emerged as particularly relevant, highlighting the increasing significance of social issues in sustainable supply chains. This finding aligns with previous studies suggesting that social mismatches often generate tension within supply chain networks [54]. Additionally, this study provides further operational insight by identifying the risk of unsafe delivery (SD 2) as critical, offering actionable guidance for risk mitigation at the operational level. Conversely, risks with more localized impact, such as community disruption (SP 2), were found to be less significant due to their limited effect on systemic sustainability.

From an environmental standpoint, climate change-induced instability in raw material supply (EP 2) was ranked among the most relevant risks. This supports earlier research indicating that environmental volatility is a major concern for global supply chains [50]. Nevertheless, this study contributes novel insights by identifying localized environmental risks—such as inadequate waste disposal infrastructure (EM 1)—that are context-specific and have not been widely addressed in previous literature.

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4.7. Risk Assessment Result with Fuzzy BWM

This research found that the economic dimension has the most significant role in sustainable supply chain risk management, as indicated by the highest global weight of 0.50. The Fuzzy BWM analysis ranked risks based on local and global weights, as presented in **Table 11**. The findings provide important insights into the risk hierarchy and show that risks in the economic dimension dominate the top concerns, followed by the social (0.29) and environmental (0.22) dimensions. This research confirms the importance of focusing on economic elements, ensuring operational sustainability.

In the economic dimension, raw material delays (ECS 1) are the top priority risk, with the highest global weight being 0.15. This finding reflects the significant impact of supply uncertainty on the continuity of the production process and operational efficiency. In addition, the risks of raw material price fluctuations (ECS 3) and production disruption due to equipment breakdown (ECM 2) have global weights of 0.12 and 0.11, respectively, confirming that cost stability and production process reliability are also important factors for supply chain sustainability.

In the social dimension, the risk of unsafe delivery (SD 2) ranks highest with a global weight of 0.13. It shows that safety in distribution affects not only customer satisfaction but also the company's overall reputation. In addition, the risk of fulfillment of workers' rights (SS 2) has a global weight of 0.09, highlighting the importance of integrating fair social standards and treatment of workers in the supply chain. Other elements, such as failure in supplier selection (SS 1) and lack of competent labor (SM 1), show that social stability in the supply chain still requires special attention despite its lower weight.

Despite having the lowest weight overall, the environmental dimension still represents a significant risk that must be managed. The risk of climate change affecting raw material supply (EP 2) has the highest global weight of 0.06. It reflects the need for adaptation to environmental changes to maintain long-term supply stability. In addition, the lack of waste disposal facilities (EM 1) with a global weight of 0.05 indicates that waste management is a top priority in supporting environmental sustainability. Other risks, such as carbon emissions from transportation (ED 2), have smaller weights but still require mitigation strategies to reduce negative environmental impacts.

Delayed arrival of raw materials (ECS 1) emerged as one of the most critical risks in sustainable supply chains due to its substantial influence on operational continuity and supply chain efficiency. Delays in raw material delivery can severely disrupt production schedules, lead to late fulfillment of customer orders, increase logistical expenses, and reduce customer satisfaction levels—all of which threaten the stability and resilience of supply chains [60]. Moreover, previous studies indicate that such delays can hinder supplier integration and negatively impact environmental performance, which are both essential components of sustainable supply chains. These disruptions can elevate strategic risk and impede an organization's ability to achieve long-term sustainability objectives [55]. Therefore, ECS 1 represents not only an operational challenge but also a long-term sustainability concern with economic, social, and environmental implications.

Another highly prioritized risk is unsafe delivery (SD 2), which poses a significant threat to supply chain sustainability through its effects on operational safety, brand reputation, and product quality. Research underscores that secure and reliable distribution is essential for sustaining overall supply chain performance. Failures in this area can result in financial losses, reputational damage, and adverse social consequences, particularly in local communities [58]. Additionally, unsafe delivery practices elevate health, safety, and environmental (HSE) risks, which can disrupt company operations and diminish supply chain resilience. These

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incidents may deteriorate customer and community trust and degrade long-term sustainable performance [56]. Furthermore, studies highlight that distribution-related risks (including unsafe delivery) can destabilize global logistics systems and intensify environmental harm through increased carbon emissions, particularly in scenarios requiring product returns, recovery, or re-shipment [63]. Accordingly, SD 2 must be managed strategically, given its direct impact on efficiency, sustainability goals, and stakeholder relationships.

Raw material price fluctuations (ECS 3) are also categorized as a top-priority risk due to their potential to destabilize financial planning, increase production costs, and undermine sustainable investment strategies. Variations in raw material prices are driven by demand shifts, resource availability, extraction efficiency, and geopolitical influences, all of which complicate supply chain operations—especially in resource-dependent industries such as renewable energy [57]. Scholars have highlighted price volatility as a major obstacle to sustainable supply chain development, particularly as it limits an organization's capacity to invest in eco-friendly technologies and long-term sustainability initiatives [58]. Furthermore, fluctuations are often exacerbated by international trade regulations and environmental policy changes, which can create additional uncertainties in global markets and complicate sourcing and production planning [66]. As such, ECS 3 represents a substantial risk to financial stability and the implementation of sustainability-driven strategies across the supply chain.

Table 11. Risk assessment results with Fuzzy BWM.

Risk Dimension	*Weight Dimension*	Risk Elements	Local Weight	Local Rank	Global Weight	Global Rank
Economic	0.50	ECP 1	0.11	4	0.60	7
		ECP 2	0.06	6	0.03	14
		ECS 1	0.29	1	0.15	1
		ECS 3	0.23	2	0.12	3
		ECM 2	0.21	3	0.11	4
		ECD 2	0.10	5	0.05	9
Social	0.29	SS 1	0.07	5	0.02	16
		SS 2	0.30	2	0.09	5
		SM 1	0.10	3	0.03	13
		SM 2	0.08	4	0.02	15
		SD 2	0.45	1	0.13	2
Environment	0.22	EP 1	0.16	4	0.04	10
		EP 2	0.26	1	0.06	6
		ES 1	0.19	3	0.04	11
		EM 1	0.22	2	0.05	8
		EM 2	0.12	5	0.03	12
		ED 2	0.05	6	0.01	17

4.8. Implication

The framework proposed in this study significantly contributes to sustainable supply chain risk management through a systematic and data-driven approach. The framework identifies and eliminates irrelevant risks by integrating Fuzzy Delphi and Fuzzy BWM methods. It provides clear priorities for significant risk elements. This approach improves the efficiency of risk analysis. It ensures companies can allocate resources more effectively to address the most impactful risks. In the context of sustainability, the framework also encourages the adoption of more proactive strategies to manage economic, social, and environmental dimensions in a balanced manner.

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Practically speaking, this framework has the potential to be widely applied in various industrial sectors, including the food, manufacturing, and logistics sectors. Its ability to handle fuzzy data and uncertainty in expert preferences makes it a reliable tool for dealing with complex operational challenges. In addition, the framework can also support policymakers in designing sustainability-focused regulations with a strong data-driven approach. By providing clear risk prioritization guidance, the framework helps organizations improve operational efficiency, reduce environmental impact, and strengthen social performance.

Theoretically, this study extends the supply chain risk management literature by integrating two fuzzy methods in one holistic framework. This approach provides an advantage over previous studies that use these methods separately. The result is a more structured, adaptive, and reliable supply chain risk management approach.

The findings of this study indicate that a framework integrating Fuzzy Delphi and Fuzzy BWM methods provides a more targeted and practical approach to sustainable supply chain risk management. Fuzzy Delphi successfully eliminated risks with relevance values below the 0.5 threshold at the risk relevance assessment stage. For example, risks such as poor raw material quality (ECS 2) and product damage during transportation (ECD 1) were considered irrelevant and excluded from further analysis. This process ensures a focus on significant risks, which is in line with the research of [48], which showed that fuzzy-based methods improve decision-making efficiency by reducing uncertainty in expert preferences. However, this study provides more specific relevance assessments based on economic, social, and environmental dimensions, giving it an edge over previous studies.

The risk assessment results using Fuzzy BWM confirmed the economic dimension as the top priority in sustainable supply chain risk management, with the highest weight of 0.50. The risk of raw material delays (ECS 1) is the sub-criterion with the highest global weight of 0.15, followed by the risk of raw material price fluctuations (ECS 3) with a weight of 0.12. This research provides an advantage by integrating sustainability aspects, which allows companies to manage economic risks and pay attention to social and environmental impacts simultaneously. On the social dimension, the risk of unsafe delivery (SD 2), with a global weight of 0.13, is the main focus, indicating that distribution safety significantly impacts the company's reputation and customer satisfaction. On the other hand, in the environmental dimension, climate change affecting the stability of raw material supply (EP 2) with a weight of 0.06 is prioritized, showing the importance of adapting to uncertain environmental dynamics.

A key advantage of these findings is their ability to provide clear prioritization guidance based on quantitative data, allowing managers to focus on the risks that impact sustainability the most. Unlike previous studies that are often limited to a one-dimensional analysis, this research offers a multidimensional approach that covers economic, social, and environmental aspects in an integrated manner. As such, companies can design more comprehensive risk mitigation strategies, ranging from improving raw material supply stability to managing social and environmental impacts.

Practically, the findings have broad application potential, particularly in sectors that face high uncertainty, such as food, manufacturing, and logistics. Companies can allocate resources more effectively using this framework to manage priority risks, improve operational efficiency, and ensure long-term sustainability. In addition, this approach is also relevant for policymakers when designing regulations that support sustainability-based risk management.

In alignment with the United Nations' 2030 Agenda, this study supports several Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate

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Action). By focusing on risk assessment in sustainable food supply chains, the research contributes to building resilient infrastructure and fostering innovation in supply chain operations that ensure food availability, reduce waste, and minimize environmental impact. The application of fuzzy-based decision-making tools not only enhances operational effectiveness but also promotes more inclusive, transparent, and sustainable practices. This alignment ensures that the findings of the study are not only academically significant but also directly relevant to achieving global sustainability targets in both economic and environmental dimensions. Finally, this study adds new information regarding SDGs, as reported elsewhere (**Table 12**).

Table 12. Previous studies on SDGs.

No	Title	Ref.
1	Sustainable packaging: Bioplastics as a low-carbon future step for the sustainable development goals (SDGs)	[59]
2	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting sustainable development goals (SDGs): A techno-economic and bibliometric analysis	[60]
3	Hazard identification, risk assessment, and determining control (HIRADC) for workplace safety in manufacturing industry: A risk-control framework complete with bibliometric literature review analysis to support sustainable development goals (SDGs)	[61]
4	Techno-economic analysis of production ecobrick from plastic waste to support sustainable development goals (SDGs)	[62]
5	Techno-economic analysis of sawdust-based trash cans and their contribution to Indonesia's green tourism policy and the Sustainable Development Goals (SDGs)	[63]
6	Definition and role of sustainable materials in reaching global Sustainable Development Goals (SDGs) completed with bibliometric analysis	[64]
7	The Journal of Engineering, Science and Technology (JESTEC): A bibliometric insight into materials research trends and innovation to support Sustainable Development Goals (SDGs)	[65]
8	Physical adaptation of college students in high-altitude training: Empirical findings and curriculum development insights to support Sustainable Development Goals (SDGs)	[66]
9	Enhancing job satisfaction through human resource information systems and communication: A commitment-based approach to achieve Sustainable Development Goals (SDGs) in education-oriented organizations	[67]
10	Enhancing innovative thinking through a theory-based instructional model in design education to support Sustainable Development Goals (SDGs)	[68]
11	Influence of self-efficacy on affective learning outcomes in social studies education toward achieving Sustainable Development Goals (SDGs)	[69]
12	Enhancing occupational identity and self-efficacy through a self-education model in art and design education aligned with Sustainable Development Goals (SDGs)	[70]
13	Integrating generative artificial intelligence (AI)-based multimodal learning in education to enhance literacy aligned with Sustainable Development Goals (SDGs)	[71]
14	Dataset on the number of schools, teachers, and students in Sulawesi, Indonesia... supporting Sustainable Development Goals (SDGs)	[72]
15	The influence of environmentally friendly packaging on consumer interest in implementing zero waste in the food industry to meet sustainable development goals (SDGs) needs	[73]
16	Implementation of sustainable development goals (SDGs) no. 12: Responsible production and consumption by optimizing lemon commodities and community empowerment to reduce household waste	[74]

Table 12 (continue). Previous studies on SDGs.

No	Title	Reference
17	Analysis of the application of mediterranean diet patterns on sustainability to support the achievement of sustainable development goals (SDGs): Zero hunger, good health and well beings, responsible consumption, and production	[75]
18	Efforts to improve sustainable development goals (SDGs) through education on diversification of food using infographic: Animal and vegetable protein	[76]
19	Safe food treatment technology: The key to realizing the sustainable development goals (SDGs) zero hunger and optimal health	[77]
20	Analysis of student's awareness of sustainable diet in reducing carbon footprint to support sustainable development goals (SDGs) 2030	[78]

5. CONCLUSION

This study concludes that integrating the Fuzzy Delphi and Fuzzy Best Worst Method (Fuzzy BWM) offers a robust and structured approach for assessing and prioritizing risks in sustainable food supply chains. By eliminating irrelevant risks and highlighting those with the most significant impact, the framework provides a focused foundation for strategic risk management. The findings emphasize the dominant role of economic risks, as well as the importance of social and environmental factors in supporting long-term sustainability. More importantly, the framework supports the achievement of the SDGs by enabling companies to address food system vulnerabilities, improve operational resilience, and align decision-making with global sustainability targets. Future research can build on this approach by integrating risk mitigation strategies and exploring their application in broader sectors and geographic contexts.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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