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Modelling risk of sustainable rice supply chain (SRSC) to achieve food security for emerging economies

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Abstract

Purpose – Rice is an essential determinant of food security in some developing countries as it has become the state's staple food. Due to its essential role, rice supplies have been studied over the years. For this reason, it is essential to ensure quantity and quality availability, safety, distribution and affordability from input suppliers, farmers and milling industries to consumers. This study aims to assess and evaluate the relationship between sustainability risk factors for each rice supply chain actor to minimise uncertainty and losses in the supply chain and achieve a sustainable rice supply chain (SRSC).

Design/methodology/approach – A total of 50 sub-risk factors for the rice supply chain, divided into four sustainability dimensions, were derived through a literature review. Next, it was identified through interviews with 12 experts in 2 stages: the first stage, reviewing the literature review results, and the second stage, finalising with Pareto analysis. Each stage produces 28 and 21 sub-risk factors. Fuzzy-decision-making trial and evaluation analysis was used to evaluate the relationship between sub-risk factors in the context of SRSC.

Findings – The sub-risk factors that need to be managed to achieve SRSC are climate change risk (floods and rainfall) from the environmental dimension (case group) and operational risk (loss of low-quality results) from the process dimension (impact group). These practical findings provide actionable insights for supply chain actors and contribute to a deeper understanding of the complexities of the rice supply chain.

Research limitations/implications – This study underscores the urgent need for a comprehensive understanding of the risks faced by all actors in the rice supply chain. Such an understanding is crucial for future research and practical applications, and it is the key to ensuring the sustainability and security of the rice supply chain.

Originality/value – To the best of the authors' knowledge, this is the first comprehensive study in the context of SRSC that evaluates the relationship between risk factors to achieve food security in developing countries.

Keywords Sustainable rice supply chain, Risk model, Food security, Emerging economies, Fuzzy-Dematel

Paper type Research paper

1. Introduction

Residents of developing countries, especially in Asia, such as Indonesia, Vietnam, Thailand, India, Pakistan and the Philippines, consume rice as their staple food (Rizal and Galih, 2022; Sustainable Rice Platform, 2023a). This makes rice food in these countries a significant

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contributor to economic growth to improve social welfare (Mangla *et al.*, 2021; Elyasi and Teimoury, 2023; Liu *et al.*, 2023). In developing countries, rice is designated as a strategic staple food because it is the commodity most widely consumed by the public, has a prominent role in shaping inflation and has a significant contribution to the formation of gross domestic product (Statistik, 2019).

Rice is a basic necessity for survival and supports the livelihoods of billions of people worldwide, where nearly 60% of those experiencing hunger depend on rice for food and income (Sustainable Rice Platform, 2023b). Rice is a commodity that supports the livelihoods of billions of people worldwide, with nearly 60% of those experiencing hunger relying on rice for food and income (Sustainable Rice Platform, 2023b). Thus, food security is critical to fulfilling these fundamental human rights in supporting regional economic prosperity (Alam *et al.*, 2023). To achieve this goal, a food security strategy is needed, consisting of four dimensions: food availability, economic and physical access, food utilisation and consistency in the long term. These dimensions are crucial in the context of the rice supply chain as they determine the quantity, quality, affordability and safety of rice from production to consumption (FAO, 2022). Therefore, to achieve food security, the availability of distribution and consumption subsystems must also interact well (Muchlisin, 2020).

Food security cannot be achieved alone; the supply chain is also responsible for promoting food security and providing the community with sustainable, affordable and safe food. Therefore, sustainable rice supply chain (SRSC) management must be a primary concern (Wibowo Putro *et al.*, 2022). To achieve a SRSC, a balanced approach is needed in ecology, society and the economy (Rajeev *et al.*, 2017; Kamble *et al.*, 2020). All stakeholders and supply chain actors ranging from suppliers, producers, millers, distributors and retailers – directly or indirectly – who are involved in sourcing, production, post-harvest stages, storage, processing and delivery (Pakdeenarong and Hengsadeekul, 2020) must have awareness and focus on sustainable supply chain management (Sharma *et al.*, 2020a).

However, designing sustainability in a smooth and stable rice supply chain is difficult for supply chain actors because of various risks and risk-driving factors (Zhao *et al.*, 2020). From the consumption side, fluctuations in food prices continue to occur, impacting the affordability and accessibility of food products for consumers, especially in developing and low-income countries (Sazvar *et al.*, 2018). From the producer side, as many as 144 million small farmers bear most of the risks of rice production (Sustainable Rice Platform, 2023a). Meanwhile, the risk or uncertainty faced by rice millers is uncertainty in the supply of grain from farmers (Catriana and Djumena, 2023). Likewise, distributors and retailers face limitations such as warehouse and transportation limitations. Not to mention customer demand, globalisation, the COVID-19 pandemic and the ongoing Russian–Ukrainian war, there have been many complexities, uncertainties, risks and challenges (Karmaker *et al.*, 2023).

Other research has also shown the challenges and complexities of these supply chains. Lomax (2016) reveals some of the challenges of sustainable rice in the global sector facing farmers, namely, resource efficiency (land, water and labour), global greenhouse gas emissions (CH_4, N_2O, CO_2), impacts on ecosystem services, soil impacts (e.g. salinisation and arsenic), impacts of pests and diseases and effects of climate change. Hussain *et al.* (2022) also state that low land productivity and climate change are significantly impacting the efficiency of the global supply chain. Gligor *et al.* (2018) underline the challenges associated with inadequate infrastructure in most developing countries: lack of professional skills, insufficient education and training at the farmer level, lack of standardisation and lack of government support for local businesses. In addition, market dynamics play an essential role in influencing the efficiency and resilience of the rice supply chain – for example, a study conducted by Das *et al.* (2023) explains the impact of fluctuating food prices on availability and distribution in global markets. Their findings suggest that market uncertainty can complicate supply chain planning and management, disrupting food availability.

Food supply chain risk management is critical for developing countries as it helps identify, assess and mitigate risks to improve supply chain performance. Supply chain risk management helps farmers, processors, distributors, wholesalers and retailers detect potential threats, improve responsiveness, increase flexibility, maintain quality and improve efficiency in timely orders. It also helps reduce supply chain risk, improving overall performance (Waqas *et al.*, 2023). Other studies also recognise that supply chain risk management improves supply chain performance by reducing operational losses, improving responsiveness and preventing disruptions (Linn and Maenhout, 2019; Munir *et al.*, 2020; Karmaker *et al.*, 2023). However, most of the existing literature focuses only on technical methods and the ability to understand, prevent, mitigate and avoid various vulnerabilities and risks in general. Limited research classifies risks and evaluates their relevance in rice sustainability within the supply chain, significantly if they are associated with food security in developing countries. Therefore, to our knowledge, this is the first study to use four-dimensional sustainability criteria to analyse and evaluate risk factors in SRSC. By taking a multi-dimensional sustainability-based approach, the study provides a more holistic and in-depth picture of the risks in SRSC. The findings of this study will be valuable for decision makers in improving SRSC performance and food security in developing countries. To fill this gap, designing SRSC risk models to achieve food security is urgent. Thus, this study was conducted to answer the following research questions:

RQ1. What are the risk factors in an SRSC in the context of food security in developing countries?

RQ2. How can risk factors in the rice supply chain context be evaluated to improve sustainability?

RQ3. How does risk factor assessment guide supply chain actors and policy-making stakeholders in formulating rice risk mitigation strategies to achieve food security in developing countries?

Answering these research questions will provide a comprehensive understanding of the identification, classification and analysis of risk factors for each supply chain actor in the developing world. This comprehensive approach is crucial for achieving SRSC and will contribute significantly. Firstly, it will enrich the risks of SRSC, providing priorities and guidelines for effective risk management, especially when resources are limited. Secondly, it will help practitioners and stakeholders formulate comprehensive and effective mitigation strategies to reduce risks and achieve long-term sustainability. Thirdly, it will guide critical risk management decisions based on the identified key risks, ensuring a thorough and rigorous supply chain risk management approach.

2. Literature review

This section explains the literature on the relationship between SRSC and food security, detailing how risk factors and sub-factors are integrated into the SRSC framework about food security. It also describes the impact of risks on each actor at each phase within SRSC. Figure 1 presents the rationale for this study, highlighting its distinctions from previous research.

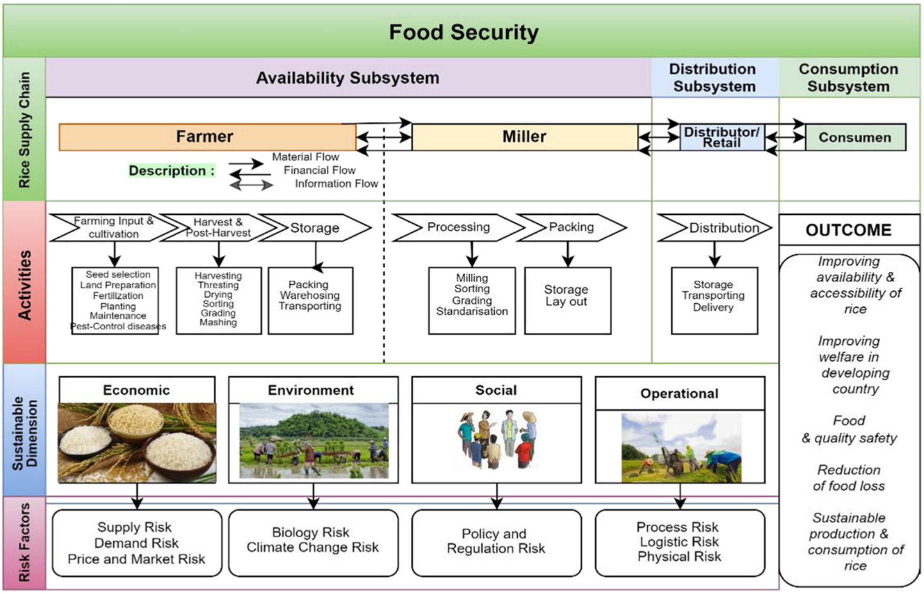

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Figure 1. Thinking frameworks

2.1 Sustainable rice supply chain and food security

Adopt the definition of sustainable supply chain management, according to Ahi and Searcy (2013), "SRSC" refers to a rice supply chain that is sustainable and coordinated through the integration of economic, environmental and social aspects. "TBL" stands for triple bottom line, a framework that evaluates a company's economic, social and environmental performance. Managing the food supply chain is crucial when it comes to food security. It has proven effective in ensuring food safety by increasing the availability and accessibility of food products (Gupta *et al.*, 2023).

Today, consumer preferences have shifted towards higher quality products, stricter quality and safety standards, short shelf life of agri-food products, lower costs and less dependence on climatic conditions (Okpiaifo *et al.*, 2020). Thus, understanding the concept of food security is essential. Food security is defined as a state where all people constantly have physical, social and economic access to sufficient, safe and nutritious food that meets their needs and preferences in pursuit of an active and healthy life (Mirzabaev *et al.*, 2023). It is essential from the food demand and farmer/producer sides. SRSC helps farmers and small-scale producers access markets and receive fair product prices (Gupta *et al.*, 2023). This not only supports the livelihoods of farmers and producers but also helps ensure the long-term sustainability of agriculture and the availability of food products (Kouki *et al.*, 2014).

2.2 Risk factors and their impact on sustainable rice supply chain

In risk management, a thorough understanding of various types of threats and their sources, risk interactions and interdependencies, risk propagation and its ripple effects impact operational performance (Sharma *et al.*, 2020b). Meanwhile, risk in the context of SRSC can be defined as the occurrence of unexpected events that can affect the process of obtaining production facilities, cultivation and processing and even disrupt storage and distribution from producers to final consumers. There are three dimensions of sustainability in looking at rice chain risks: economic, environmental and social (Elyasi and Teimoury, 2023). At the same time, Paul *et al.* (2023) state that these four sustainability dimensions are economic, environmental, social and ethical. They are used to view supply chain uncertainty. To identify risk factors in an SRSC to achieve food security, it is necessary to consider the TBL (Zhao *et al.*, 2020). Other research divides food supply chain risks into nine: supply, demand, biological and environmental, political and macroeconomic, weather, logistics and infrastructure, policy and regulatory, financial, management and operational risks (Sharma *et al.*, 2020b). Singla and Sagar (2012) discuss agricultural risks from the perspective of key supply chain players, particularly farmers, including price risk.

This study formulates comprehensive risk factors in the SRSC for each actor, based on prior research on rice and food security, evaluated through the four dimensions of sustainability to guide strategies for minimising risks and ensuring food security. The first dimension is economic sustainability. This dimension aims to reduce supply chain costs related to physical resources, capital and price (Paul *et al.*, 2023). To achieve sustainability from an economic perspective, the rice supply chain in this study must face risks from the supply, demand, financial, price and market sides. The second dimension is environmental sustainability. This dimension is related to the preservation of two significant natural resources, namely, land and water, which is one of the most attractive ecological sustainability goals in the agri-food supply chain (Hajimirzajan *et al.*, 2021). To achieve environmental sustainability, the rice supply chain in this study faces biological risks, climate change and natural disasters. The third dimension is social sustainability. This dimension relates to community health and safety conditions, financial support and loans (Elyasi and Teimoury, 2023). To achieve social sustainability, the rice supply chain in this study faces policy, regulatory and institutional risks. The fourth dimension is operational sustainability. This dimension helps assess sustainability from a technical perspective related to creating, distributing and storing products in the supply chain (Paul *et al.*, 2023). To achieve sustainability from an operational standpoint, the rice supply chain in this study faces process, logistical and physical risks.

2.3 Related work and research gaps

Most research on risks in the rice supply chain focuses on economic and logistical aspects, while the sustainability dimension needs to be addressed (Nga, 2021). While food supply chain risks are widely studied, large-scale analyses specific to rice are limited (Zhao *et al.*, 2020; Ramos *et al.*, 2021). This study addresses this gap by analysing risks impacting rice supply chain sustainability.

Table 1 shows that various quantitative and qualitative research methods have been applied to assess, control and mitigate the adverse effects of SRSC risk, including mathematical programming (Sholihah *et al.*, 2018; Pakdeenarong and Hengsadeekul, 2019; Bairagi *et al.*, 2020; Mai *et al.*, 2022; Rath *et al.*, 2022). However, this method cannot be applied in this study because it cannot see the relationship between the risks. Variations of the multi-criteria decision analysis method have also been used in previous studies related to identifying SRSC risks, e.g. F-analysis hierarchy process (AHP), F-technique for order preference by similarity to ideal solution (TOPSIS) and best–worst method (BWM) (Pakdeenarong and Hengsadeekul, 2020; Wahyuningtyas *et al.*, 2021; Das *et al.*, 2023; Mohsin *et al.*, 2024).

Although these methods have advantages in analysing SRSC risk, each has limitations. For example, AHP ineffectively evaluates risk and uncertainty because it considers the

Table 1. Typical research methods for SRSC risks (2014–2024)

No.	Author(s) (year)	Topic focus	Methods used	Qualitative/ quantitative	Theoretical/ empirical
1	Lam *et al.* (2015a)	Risk assessment and mitigation	Value chain analysis	Qualitative	Theoretical
2	Paul and Ifeyinwa (2016)	Risk analysis and mitigation	Literature review	Qualitative	Theoretical
3	Usman *et al.* (2017)	Risk identification and mitigation	Attitudinal scale approach (ASA)	Qualitative	Empirical
4	Sirisupluxana and Bunyasiri (2018)	Risk analysis	Logistic distribution function	Quantitative	Empirical
5	Sholihah *et al.* (2018)	Risk analysis and mitigation	Multiple linear regression analysis (Just and Pope)	Quantitative	Empirical
6	Guritno *et al.* (2018)	Risk analysis and mitigation	Case study	Qualitative	Empirical
7	Prabowo *et al.* (2019)	Risk identification and analysis	Mathematical models	Quantitative	Empirical
8	Pakdeenarong and Hengsadeekul (2019)	Risk analysis	Structural equation modelling (SEM)	Quantitative	Empirical
9	Astuti *et al.* (2019)	Risk identification and mitigation	Failure mode and effect analysis (FMEA)	Quantitative	Empirical
10	Bairagi *et al.* (2020)	Risk evaluation and mitigation	Endogenous switching regression (ESR)	Quantitative	Empirical
11	Pakdeenarong and Hengsadeekul (2020)	Risk identification and mitigation	Best–worst method (BMW)	Qualitative	Empirical
12	Wahyuningtyas *et al.* (2021)	Risk identification and mitigation	Fuzzy-analysis hierarchy process (AHP)	Qualitative	Empirical
13	Rath *et al.* (2022)	Risk identification and mitigation	Structural equation modelling (SEM)	Quantitative	Empirical
14	Mai *et al.* (2022)	Risk analysis	SEM	Quantitative	Empirical
15	Das *et al.* (2023)	Risk identification and analysis	Exploratory factor analysis (EFA), fuzzy-AHP, fuzzy-technique for order preference by similarity to ideal solution (TOPSIS)	Qualitative	Empirical
16	Vinci *et al.* (2023)	Risk identification	Literature review	Qualitative	Theoretical
17	Mohsin *et al.* (2024)	Risk identification and mitigation	Fuzzy-AHP	Qualitative	Empirical

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importance of relative risk and is unable to assess relationships among risk factors (Ali *et al.*, 2019). Whereas in real life, the relationship between supply chain risk factors exists, and one factor will be able to influence another. The decision-making trial and evaluation (Dematel) can be used in this study to characterise the relationship. Dematel captures causal relationships among supply chain risk factors, clarifying ambiguities for decision makers. In this study, Dematel structures SRSC risks into cause-effect groups via causal diagrams, aiding in understanding complex risk interactions for better management (Lin, 2013). Based on the literature review, several research gaps can be identified, which are the novelty of this study, as follows:

- Although SRSCs play an essential role in the world's economy as a primary source of food supply, there are significant shortcomings in empirical studies identifying SRSC risks. Literature review articles in the past 10 years (2014–2024) that considered risks in SRSC showed only 17 out of 87 articles (Table 1). Moreover, nothing has been linked to food security, even more so for developing countries. This indicates an apparent demand for research related to empirical SRSC risk analysis. Therefore, this finding became the novelty of this study.
- Existing studies primarily focus on risk analysis, assessment and mitigation. However, studies defining correlations among different SRSC risks still need to be completed. Further research is required to investigate the relationship between the various risks of SRSC because the effect of one risk interacting with another risk can result in the loss of substantial (Chopra and Sodhi, 2004).
- The Dematel method has been widely used in various sectors to solve decision-making problems. However, it has been in-explicitly used in research with risk topics in SRSC, such as Ali *et al.* (2019) using Pareto and Dematel to analyse interrelationships between food supply chain risks. Lin (2013) presented fuzzy-Dematel to evaluate green supply chain management practices. Benabdallah *et al.* (2020) used the Dematel approach to assess the agricultural food supply chain risks and consider the interrelationship between different risks in different groups. The fuzzy integration of Delphi and Dematel approaches is used to analyse the interrelationships among risk elements in the kosher supply chain (Khan *et al.*, 2021)). Furthermore, Mathiyazhagan *et al.* (2020) conducted a risk analysis of a green supply chain in an industrial context in India with Dematel. Next, Benabdallah *et al.* (2022) evaluate supply chain failures by analysing the interrelationship between sustainability and risk factors with Dematel in the dairy industry. It can be said that the novelty of this study lies in the analysis used to analyse the interrelationship of SRSC risks in developing countries in food security efforts, using Dematel, which has yet to be done in previous studies. Thus, this study's findings can help fill the above research gaps.

3. Research methodology

3.1 Integrated approach

The Dematel method is applies the multi-criteria dimension model (MCDM) technique to create causal diagrams of interdependent elements (Lin, 2013). The advantage of Dematel is that it is a suitable method for exploring causal relationships between criteria, visualising the influence of criteria as a whole and analysing dependent criteria in multi-criteria decision problems (Du and Li, 2021). Dematel can also link their relationships' risks and strengths (Khan *et al.*, 2021) and shows some weaknesses caused by the possibility of a nonconvergent total relationship matrix, uncertainty of subjective cognition and arbitrariness of subjective evaluation (Khan and Haleem, 2020). To address these issues, fuzzy set theory is combined with Dematel, enhancing its capacity to manage uncertainties, especially in cases with limited problem information (Du and Li, 2021). By combining fuzzy set theory, this assessment preserves human judgement by converting linguistic preferences into fuzzy numbers (Lin, 2013). Before implementing Fuzzy-Dematel, Pareto analysis is used to identify the most important drivers for implementing SRSC. This is due to the Pareto analysis's simplicity and ability to prioritise essential factors without pairwise assessment, reducing opinion bias (Karmaker *et al.*, 2021).

3.2 Survey design

This survey was carried out in several stages, from determining experts to collecting data on determining risk dimensions, factors and sub-factors and the analytical tools used (Figure 2).

3.3 Determination of experts

This study requires experts to deliver insights and information on determining sub-risk factors – starting from the literature review results, determining the Likert scale in Pareto analysis and finally determining the relationship between two sub-risk factors applying linguistics approaches. Experts selection used purposive sampling with specific considerations to obtain experts' qualitative views expected to achieve the study's objective (Akter *et al.*, 2022). The criteria for specific consideration determining experts are based on job position, experience and in-depth knowledge related to rice risks and sustainable supply chains. As a result, 12 experts were chosen to participate in this study, including academics,

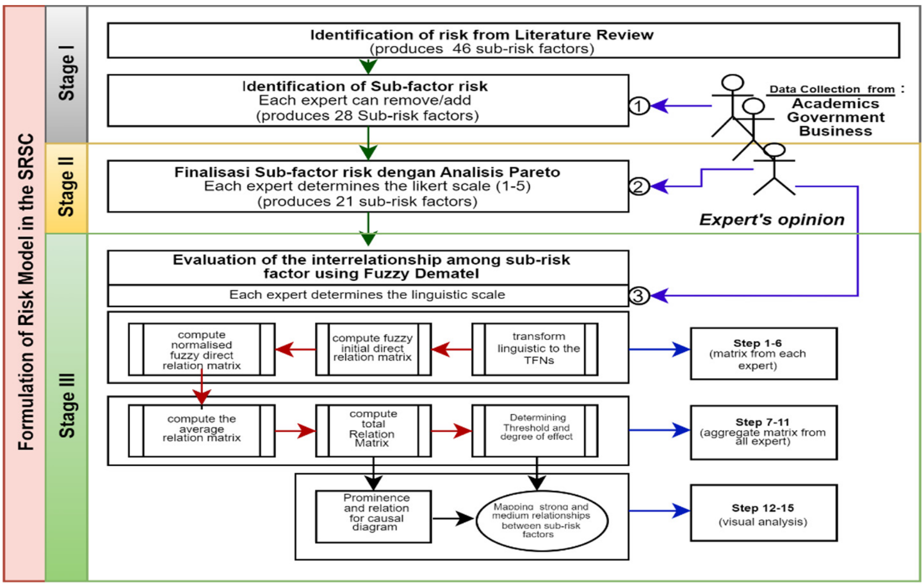

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Figure 2. Research structures

professionals, related agencies, extension workers and representatives from farmer groups. The respondent profiles are presented in Appendix Table A4.

3.4 Data/information collection

- Experts' views-based data were collected from May to July 2023. The data were obtained through expert interviews using questionnaires that had been prepared in advance. The collected data after sub-risk factors associated with SRSC were identified based on a literature review. The data collection from experts was collected thrice in stages: each expert validates whether the sub-risk factors resulting from the literature review are relevant in the context of SRSC. Appendix Table A1 presents questionnaires used to assess sub-risk factors. In this stage, all experts were required to give an opinion on whether they agreed with the sub-risk factors resulting from the literature review. Apart from that, they were also free to add and subtract these sub-risk factors.
- Each expert was asked to provide their opinion through a Likert scale questionnaire to measure the weighting of sub-risk factors used in Pareto analysis. Appendix Table A2 presents a questionnaire used to perform a Pareto analysis that is redistributed to the same 12 experts.

This analysis was used to identify sub-risk factors relevant to SRSC practice. Different researchers have applied various types of Likert scales. A 0–5 Likert scale can be used to identify significant rice supply chain sub-risk factors (Ali *et al.*, 2019). After collecting expert responses, a cumulative score of around 80% is calculated, and the relevant sub-factors are selected for further analysis.

- Each expert was asked to provide their opinion again via a linguistic scale questionnaire to evaluate the relationship between the two risk factors in the Fuzzy-Dematel analysis.

3.5 Model formulation

The risk factor model in SRSC was built using the integration of Pareto and Fuzzy-Dematel analysis. The model formulation is carried out through three stages, from determining sub-risk factors to modelling the relationship between risks, visualised using causal diagrams.

3.5.1 Stage I: Risk identification. At this stage, there are two parts:

(1) Firstly, the identification of risk factors and sub-factors based on sustainability dimensions through the assessment of academic literature, articles and websites related to SRSC (Table 2). Rice supply chain actors face 43 risk factors from several developing countries, which are divided into four sustainability dimensions (economic dimension, environmental dimension, social dimension and operational dimension) and ten risk factors (supply risk, demand risk, price and market risk; biological risks; climate change risks; and policy and regulatory risks;

(2) Secondly, experts verified the relevance of 43 sub-risk factors that were identified based on the literature review. Experts are free to add/reduce/approve those risk sub-factors. After the experts provided feedback from the literature, 28 sub-factors were left consisting of 24 approved sub-factors and 4 risk sub-factors were added by the experts: low quality of supplier, limited irrigations, limited knowledge of good agriculture practice (GAP) and good manufacturing process (GMP) and damage during storage. Meanwhile, 19 sub-risk factors were removed due to low relevance (Table 2) and expert consideration input on factors like actor characteristics in the rice supply chain, policies, supporting facilities and consumer preferences in the study location.

Table 2. Identify risk factors and sub-factors based on the sustainability dimensions of SRSC from literature and after expert validation

	Risk factor in SRSC	Impact of risk in activities along rice SC phase: A	B	C	D	E	F	G	References	Expert feedback
Economic dimensions										
A. Demand risk										
R1	limited production input	√	√	√	√	√	√	√	(Ramos *et al.*, 2021; Rath *et al.*, 2022; Ullya *et al.*, 2022)	Approved
	limited production input	√	√						(Pakdeenarong and Hengsadeekul, 2019; Zhao *et al.*, 2020; Sabila *et al.*, 2022)	Removed
R2	Limited agricultural tools and machinery		√	√	√				(Paul and Ifeyinwa, 2016; Nazir *et al.*, 2018; Sherif *et al.*, 2020)	Approved
R3	Low quality of suppliers									Added
B. Supply risk										
	Distortion of information	√			√	√		√	(Usman *et al.*, 2017; Karabas *et al.*, 2018; Wang *et al.*, 2020; Rathore *et al.*, 2021; Waqas *et al.*, 2022)	Removed
R4	Inconsistency between demand and forecast	√			√	√		√	(Karabas *et al.*, 2018; Nga, 2021; Tavakoli and Abadi, 2023)	Approved
	Consumer preferences for rice change throughout the year	√	√		√			√	(Linn and Maenhout, 2019; Nga, 2021)	Removed
R5	Changing needs for healthy and safe food	√	√		√	√	√	√	(Nyamah *et al.*, 2017; Sharma *et al.*, 2020b; Mangla *et al.*, 2021; Dang and Pham, 2022)	Approved
C. Piece and market										
R6	Input price uncertainty	√	√	√	√	√	√		(Anthony Lam *et al.*, 2015b; Benabdallah *et al.*, 2020; Lien *et al.*, 2022)	Approved
R7	Input price uncertainty			√	√				(Sirisupluxana and Bunyasiri, 2018; Rath *et al.*, 2022)	Approved
	Market uncertainty in terms of quality and quantity	√	√	√	√	√	√	√	(Yeboah *et al.*, 2014; Keramydas *et al.*, 2015; Rohmah *et al.*, 2015; Waqas *et al.*, 2022)	Removed
	Market uncertainty in terms of quality and quantity								(Karmaker *et al.*, 2023)	Removed
R8	High input prices	√			√				(Karmaker *et al.*, 2023; Paul *et al.*, 2023)	Approved
Environmental dimensions										
D. Biology										
R9	Irrigation limitations	√	√	√						Added
R10	Excessive heavy metals in the soil (use of fertilisers, pesticides and other chemicals)		√		v				(Pakdeenarong and Hengsadeekul, 2019; Komarek *et al.*, 2020; Ullya *et al.*, 2022)	Approved
R11	Plant pests and diseases		√						(Nazir *et al.*, 2018; Guritno *et al.*, 2019; Komarek *et al.*, 2020; Lien *et al.*, 2022; Oliveira *et al.*, 2023)	Approved
	Greenhouse gas emissions								(Okpiaifo *et al.*, 2020)	Removed
	Contamination related to food safety (bleaching and rice husks)	√	√	√	√	√	√	√	(Elyasi and Teimoury, 2023)	Removed

(*continued*)

Table 2. Continued

	Risk factor in SRSC	Impact of risk in activities along rice SC phase A	B	C	D	E	F	G	References	Expert feedback
E. Climate change										
R12	Flood	√	√	√	√	√		√	(Yazdani *et al.*, 2019; Bairagi *et al.*, 2020; Pakdeenarong and Hengsadeekul, 2020)	Approved
	Extreme winds	√	√	√				√	(Sharma *et al.*, 2020b; Ullya *et al.*, 2022)	Removed
R13	Excess/deficit rainfall	√	√	√				√	(Sharma *et al.*, 2020b	Approved
	Extreme drought	√	√	√				√	(Dang and Pham, 2022; Ullya *et al.*, 2022)	Removed
	The emergence of disturbing situations such as pandemics, earthquakes and wars								(Karmaker *et al.*, 2023)	Removed
Social dimension										
F. Policy and regulatory risks										
R14	Uncertain trade and market policies	√	√	√	√	√	√	√	(Yazdani *et al.*, 2019; Karmaker *et al.*, 2023; Zhai *et al.*, 2023)	Approved
R15	Unpredictable policies and regulations	√	√	√	√	√	√	√	(Anthony Lam *et al.*, 2015b; Surya *et al.*, 2015; Nga, 2021)	Approved
	Uncertain monetary, fiscal and tax policies	√	√	√	√	√	√	√	(Sharma *et al.*, 2020b; Ramos *et al.*, 2021; Dang and Pham, 2022)	Removed
G. Institutional risk										
	Lack of skills and experience in production	√	√	√	√				(Benabdallah *et al.*, 2020; Dang and Pham, 2022)	Removed
R16	Limited role of cooperative institutions, extension workers, farmer groups, etc	√	√	√	√				(Alam *et al.*, 2020; Sabila *et al.*, 2022)	Approved
	Occupational health and safety equipment	√	√	√	√				(Chen *et al.*, 2013; Karmaker *et al.*, 2023)	Removed
R17	Limited financial support								(Ren *et al.*, 2021)	Approved
Operational dimension										
H. Processing risk										
R18	Loss of yields			√	√	√			(Anthony Lam *et al.*, 2015b; Komarek *et al.*, 2020)	Approved
	Low capacity of the milling machine				√	√			(Babu *et al.*, 2021; Sabila *et al.*, 2022)	Removed
R19	Low capacity of the milling machine			√	√	√			(Rohmah *et al.*, 2015; Surya *et al.*, 2015; Karabas *et al.*, 2018; Pakdeenarong and Hengsadeekul, 2020)	Approved
R20	Limited knowledge of *good agriculture practice* (GAP) and *good manufacturing process* (GMP)	√	√		√					Added
I. Financial risk										
	Uncertain interest rate and exchange rate policies	√	√	√	√				(Karabas *et al.*, 2018; Waqas *et al.*, 2022)	Removed
	Slow return on assets								(Paul *et al.*, 2023)	Removed

(*continued*)

Table 2. Continued

	Risk factor in SRSC	Impact of risk in activities along rice SC phase A	B	C	D	E	F	G	References	Expert feedback
R21	Uncertainty of financial support (agricultural contracts and credit support)	√	√	√	√	√			(Ramos *et al.*, 2021; Dang and Pham, 2022; Rath *et al.*, 2022)	Approved
R22	Delays in accessing financial support	√	√	√	√				(Waqas *et al.*, 2022)	Approved
J. Logistic										
	Low logistics performance					√	√	√	(Yeboah *et al.*, 2014; Sharma *et al.*, 2020b; Tavakoli and Abadi, 2023)	Removed
R23	Limited stock-level information	√	√	√	√	√			(Rohmah *et al.*, 2015; Linn and Maenhout, 2019)	Approved
R24	Limited storage/warehousing					√		√	(Nga, 2021; Krstić *et al.*, 2023)	Approved
R25	Poor packaging (limitations in the application of green packing)						√		(Pakdeenarong and Hengsadeekul, 2019; Krstić *et al.*, 2023)	Approved
R26	Damage during storage					√		√		Added
K. Physical infrastructure (private/public)										
	Limited infrastructure and services (electricity, water, etc.)	√	√	√	√	√	√	√	(Nga, 2021; Rath *et al.*, 2022)	Removed
R27	Poor road access and conditions					√		√	(Zhai *et al.*, 2023)	Approved
	Gas emissions during delivery					√	√	√	(Connor *et al.*, 2022)	Removed
R28	Damage during shipping					√	√	√	(Nga, 2021)	Approved

Notes: Information A = farming input; B = cultivation; C = harvest and post-harvest; D = processing; E. storage; F = packing; G = distributor and retail
Source: Created by authors

3.5.2 Stage II: Risk finalisation using Pareto analysis. Pareto analysis is carried out to help interested stakeholders obtain the most relevant sub-risk factors in the context of SRSC. It is based on the 80/20 rule, which states that 80% of results result from 20% of causes (Alam *et al.*, 2023). Based on the concept of Pareto analysis, 80% of the cumulative percentage is the limit for selecting risk factors. Therefore, what remains will be ignored. The results of the Pareto analysis revealed that seven sub-risk factors among 28 were ignored in the SRSC context. The sub-risk factors are:

- R15: Unpredictable policies and regulations;
- R17: Limited financial support;
- R22: Delay in accessing financial assistance;
- R23: Limited stock-level information;
- R24: Limited storage/warehouse;
- R25: Poor packing; and
- R28: Damage in shipping.

3.5.3 Stage III: Evaluate the relationship between sub-risk factors using Fuzzy-Dematel analysis. After sorting the relevant sub-factors using Pareto analysis, the remaining 21 sub-risk factors are presented in Appendix Table A5. Next, Dematel analysis uses fuzzy to evaluate the relationship between the identified SRSC sub-risk factors and build a risk model to produce a cause and impact diagram. For this purpose, 12 experts were asked to repeat the same questionnaire.

The following is the gradual implementation of Fuzzy-Dematel, which was adopted by Khan *et al.* (2021).

- Twelve experts were asked for their opinions to assess the relationship between the sub-risk factors for each expert. The initial direction relation matrix was produced, shown in Table A7.
- The linguistic information is then interpreted into a fuzzy linguistic scale. Here, experts use different linguistic terms to express the relationship of the two sub-risk factors shown in Tabel D1. So, the fuzzy initial direct relation matrix will be produced.
- The 12 fuzzy initial direct relation matrices are converted into normalised fuzzy direct relation matrices with equation (D1) (Appendix 4). Then, equations (D2)–(D4) (Appendix 4) convert linguistic information into triangular fuzzy numbers (TFNs) in crisp values and integrate crisp values from 12 expert opinions.
- Then combine/aggregate the normalised fuzzy direct relation matrix from all experts through equation (D5) (Appendix 4). After that, the normalised direct matrix (O) is generated via equations (D7) and (D8) (Appendix 4). The total relation matrix T is declared an identity matrix when matrix O is generated. The total relation matrix T is calculated using equation (D9) (Appendix 4). This matrix is shown in Table 3.
- Based on the total relation matrix (T), a causal diagram is also produced using equations (D10) and (D11) (Appendix 4), namely, through the sum of the columns (D) and the sum of the rows (R). The horizontal axis vector (D + R) is called prominence, resulting from adding D and R. This value also shows how vital the sub-risk factors are. Meanwhile, the relation is the vertical axis vector (D − R), the result of subtracting D and R. This value shows how much it influences other sub-

Table 3. Total relation matrix (T) for sub-factor risk

Risk SF	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R16	R18	R19	R20	R21	R26	R27	D
R1	0.33	0.19	0.32	0.24	0.24	0.12	0.35	0.34	0.11	0.20	0.21	0.17	0.16	0.17	0.28	0.42	0.43	0.19	0.30	0.33	0.26	5.35
R2	0.18	0.20	0.17	0.15	0.14	0.12	0.22	0.22	0.07	0.12	0.15	0.11	0.10	0.14	0.20	0.30	0.28	0.10	0.14	0.22	0.13	3.45
R3	0.29	0.16	0.30	0.22	0.22	0.10	0.33	0.32	0.08	0.19	0.18	0.14	0.14	0.16	0.26	0.37	0.40	0.17	0.27	0.33	0.22	4.84
R4	0.24	0.19	0.25	0.25	0.24	0.11	0.26	0.25	0.09	0.17	0.17	0.13	0.12	0.16	0.22	0.32	0.32	0.16	0.22	0.27	0.18	4.31
R5	0.18	0.13	0.17	0.20	0.21	0.06	0.17	0.17	0.06	0.14	0.11	0.09	0.08	0.13	0.19	0.21	0.23	0.14	0.17	0.23	0.13	3.20
R6	0.14	0.11	0.13	0.11	0.11	0.15	0.21	0.21	0.05	0.10	0.11	0.08	0.09	0.09	0.15	0.26	0.25	0.09	0.12	0.17	0.10	2.82
R7	0.24	0.14	0.24	0.16	0.17	0.10	0.29	0.28	0.07	0.14	0.17	0.11	0.11	0.13	0.21	0.34	0.33	0.14	0.22	0.24	0.19	4.00
R8	0.20	0.15	0.20	0.18	0.17	0.11	0.29	0.28	0.07	0.15	0.16	0.12	0.12	0.14	0.23	0.35	0.34	0.12	0.19	0.28	0.19	4.05
R9	0.19	0.15	0.18	0.16	0.17	0.10	0.22	0.21	0.08	0.14	0.15	0.13	0.12	0.14	0.19	0.31	0.29	0.13	0.15	0.23	0.14	3.58
R10	0.24	0.18	0.24	0.21	0.21	0.12	0.27	0.26	0.08	0.21	0.18	0.13	0.13	0.17	0.28	0.36	0.36	0.18	0.19	0.32	0.15	4.45
R11	0.26	0.21	0.24	0.21	0.21	0.13	0.32	0.31	0.09	0.24	0.23	0.13	0.12	0.24	0.30	0.39	0.39	0.15	0.20	0.31	0.18	4.85
R12	0.36	0.26	0.34	0.29	0.32	0.13	0.39	0.40	0.18	0.28	0.22	0.25	0.18	0.23	0.38	0.50	0.51	0.20	0.33	0.39	0.29	6.42
R13	0.32	0.22	0.31	0.27	0.29	0.20	0.39	0.39	0.18	0.28	0.21	0.26	0.23	0.23	0.36	0.48	0.49	0.19	0.28	0.36	0.24	6.20
R14	0.16	0.14	0.16	0.14	0.14	0.07	0.16	0.17	0.07	0.19	0.15	0.09	0.09	0.20	0.24	0.26	0.26	0.11	0.14	0.23	0.11	3.29
R16	0.20	0.17	0.20	0.19	0.21	0.09	0.23	0.24	0.08	0.20	0.19	0.13	0.12	0.20	0.28	0.33	0.34	0.15	0.18	0.28	0.15	4.14
R18	0.26	0.21	0.25	0.20	0.23	0.09	0.23	0.22	0.15	0.25	0.16	0.13	0.12	0.16	0.22	0.33	0.31	0.15	0.23	0.26	0.20	4.35
R19	0.18	0.14	0.17	0.15	0.15	0.07	0.17	0.17	0.09	0.21	0.14	0.11	0.11	0.19	0.19	0.27	0.26	0.11	0.15	0.22	0.13	3.39
R20	0.22	0.16	0.21	0.22	0.24	0.07	0.22	0.20	0.07	0.13	0.15	0.09	0.09	0.13	0.17	0.24	0.26	0.20	0.24	0.26	0.19	3.73
R21	0.29	0.15	0.29	0.21	0.22	0.08	0.29	0.29	0.07	0.16	0.15	0.14	0.13	0.15	0.22	0.31	0.35	0.17	0.27	0.28	0.24	4.45
R26	0.24	0.18	0.24	0.21	0.22	0.09	0.27	0.26	0.08	0.17	0.17	0.15	0.14	0.18	0.23	0.29	0.33	0.20	0.20	0.31	0.16	4.30
R27	0.26	0.15	0.24	0.19	0.19	0.08	0.27	0.24	0.06	0.14	0.15	0.11	0.11	0.13	0.19	0.29	0.29	0.17	0.24	0.24	0.22	3.95
R	*4.94*	*3.55*	*4.83*	*4.15*	*4.31*	*2.18*	*5.55*	*5.41*	*1.86*	*3.79*	*3.52*	*2.79*	*2.61*	*3.47*	*4.99*	*6.92*	*7.02*	*3.22*	*4.44*	*5.76*	*3.79*	TV = 0.202

Source: Created by authors

risk factors and is included in the cause category (Table 4). If (D − R) is negative, the sub-risk factors will be grouped into the impact category.

- A cause and impact diagram can be produced by mapping the data set from (D + R, D − R). Placing the position of each sub-risk factor within the entire system will determine which sub-risk factors most influence the system, and improvements can be made in the future. If the sub-factor risk is in the causal area located in the upper right corner, then it is a determining factor to influence the effect sub-factor. While sub-factors are in the impact area, these sub-risk factors cannot be corrected by themselves but need to manage the causal sub-risk factors to influence improvement (Figure 3).
- According to Table 3. The total relation matrix (T) obtained the threshold value (TV). This value is used to identify the impact between sub-risk factors (Table 5). If the original value in T is greater than the TV, then the sub-risk factors automatically have an effect. There are three levels of impact, namely, weak, medium and robust.

4. Finding

After going through Pareto analysis, 21 sub-risk factors were finalised. It was then continued with Fuzzy-Dematel analysis to evaluate the relationship between the sub-risk factors of SRSC.

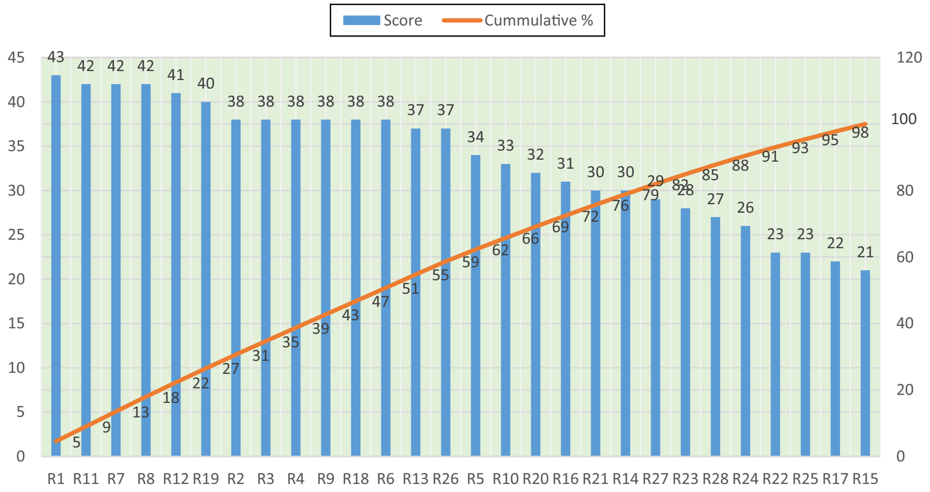
4.1 Evaluate the association between sub-risk factors

The D + R value shows the level of importance of all sub-risk factors (see Table 3). The level of importance is determined from the top five, namely, R18 (11.27) > R19 (10.41) > R1

Table 4. Prominence and relation for cause-effect

Risk sub-factor	D	R	D + R	D − R	Cause/effect
R1	5,347	4,944	10,291	0.403	*Cause*
R2	3,449	3,553	7,002	−0.103	*Effect*
R3	4,843	4,829	9,672	0.014	*Cause*
R4	4,308	4,153	8,461	0.155	*Cause*
R5	3,196	4,313	7,509	−1,116	*Effect*
R6	2,819	2,179	4,998	0.639	*Cause*
R7	3,997	5,547	9,543	−1,550	*Effect*
R8	4,050	5,411	9,460	−1,361	*Effect*
R9	3,579	1,862	5,441	1,717	*Cause*
R10	4,450	3,788	8,238	0.662	*Cause*
R11	4,846	3,524	8,370	1,323	*Cause*
R12	*6,421*	2,791	9,211	*3,630*	*Cause*
R13	*6,200*	2,611	8,812	*3,589*	*Cause*
R14	3,293	3,470	6,763	−0.177	*Effect*
R16	4,145	4,991	9,136	−0.846	*Effect*
R18	4,355	6,917	*11,272*	−2,562	*Effect*
R19	3,394	7,024	*10,418*	−3,631	*Effect*
R20	3,731	3,217	6,948	0.514	*Cause*
R21	4,453	4,439	8,891	0.014	*Cause*
R26	4,296	5,761	10,057	−1,466	*Effect*
R27	3,946	3,794	7,740	0.152	*Cause*

Source: Created by authors



Source: Created by authors

Figure 3. Pareto diagram

(10.29) > R26 (10.06) > R3 (9.67). R18 (yield loss) and R19 (low production quality) have the highest significance among other sub-risk factors. Meanwhile, the lowest level of importance of the sub-risk factors selected from the five is R6 (4.99) < R9 (5.44) < R14 (6.76) < R20 (6.94) < R2 (7.00). R6 (uncertainty of input prices) and R9 (limited water availability) have the lowest significance among other sub-risk factors.

Based on the D − R value, sub-risk factors in the SRSC are categorised as either cause or impact. Twelve sub-risk factors fall into the cause category (R1, R3, R4, R6, R9, R10, R11, R12, R13, R20, R21 and R27), while nine 9 are categorised as impact. They should be evaluated since the cause factors affect the entire system and rice supply chain sustainability. Furthermore, among all sub-risk factors in the cause category, flooding (R12) has the highest D − R value at 3.63 and the highest influence level (D) at 6.42, making it the top priority for attention in SRSC practices for community food security. The next highest sub-risk factor is rainfall (R13), with an R − D value of 3.59 and an impact level of 6.20. Thus, managing R12 and R13 is essential for rice supply chain actors, especially farmers, to reduce risk impacts.

Sub-factors in the effect group tend to be easily influenced by other sub-factors, which makes the effect sub-factor unsuitable as a determining factor for success. However, it is still necessary to discuss the impact categories to discover the characteristics of each sub-risk factor.

Among the nine sub-risk factors included in the impact category, yield loss (R18) and low yield quality (R19), where D + R has the highest top two values of 11.27 and 10.43, respectively. This shows that these two sub-factors are the most important. Unfortunately, the D − R values are the smallest, reaching −2.56 and −3.63, respectively, among all sub-risk factors in the impact category. To explain this vital finding further, looking at the value of the level of impact influenced (R), the two sub-risk factors have the highest values, respectively, 6.92 and 7.02. Thus, although R18 and R19 are impact categories, they can still influence other sub-risk factors in the system.

Table 5. Impact matrix

Risk SF	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R16	R18	R19	R20	R21	R26	R27
R1	0.326	0.000	0.317	0.241	0.244	0.000	0.349	0.343	0.000	0.000	0.213	0.000	0.000	0.000	0.267	0.416	0.426	0.000	0.300	0.327	0.260
R2	0.000	0.000	0.000	0.000	0.000	0.000	0.224	0.223	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.299	0.283	0.000	0.000	0.223	0.000
R3	0.288	0.000	0.299	0.216	0.218	0.000	0.326	0.318	0.000	0.000	0.000	0.000	0.000	0.000	0.263	0.369	0.400	0.000	0.275	0.332	0.223
R4	0.237	0.000	0.245	0.249	0.243	0.000	0.263	0.246	0.000	0.000	0.000	0.000	0.000	0.000	0.221	0.316	0.324	0.000	0.220	*0.272*	0.000
R5	0.000	0.000	0.000	0.000	0.214	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.209	0.227	0.000	0.000	0.233	0.000
R6	0.000	0.000	0.000	0.000	0.000	0.000	0.207	0.206	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.257	0.253	0.000	0.000	0.000	0.000
R7	0.242	0.000	0.239	0.000	0.000	0.000	0.292	0.283	0.000	0.000	0.000	0.000	0.000	0.000	0.208	0.337	0.328	0.000	0.217	0.235	0.000
R8	0.000	0.000	0.000	0.000	0.000	0.000	0.291	0.280	0.000	0.000	0.000	0.000	0.000	0.000	0.229	0.349	0.343	0.000	0.000	0.281	0.000
R9	0.000	0.000	0.000	0.000	0.000	0.000	0.218	0.212	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.310	0.291	0.000	0.000	0.233	0.000
R10	0.238	0.000	0.238	0.209	0.210	0.000	*0.267*	0.258	0.000	0.207	0.000	0.000	0.000	0.000	0.278	0.358	0.362	0.000	0.000	0.318	0.000
R11	0.255	0.208	0.237	0.214	0.206	0.000	0.320	0.308	0.000	0.242	0.234	0.000	0.000	0.236	0.300	*0.388*	*0.386*	0.000	0.202	0.310	0.000
R12	0.363	0.264	0.342	0.287	0.324	0.000	0.392	0.396	0.000	0.278	0.220	0.247	0.000	0.230	0.376	*0.496*	*0.507*	0.204	0.332	*0.388*	0.287
R13	0.324	0.220	0.309	0.273	0.290	0.205	0.389	*0.391*	0.000	0.283	0.212	0.259	0.234	0.227	0.359	*0.479*	*0.492*	0.000	0.282	0.356	0.245
R14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.244	0.262	0.263	0.000	0.000	0.229	0.000
R16	0.000	0.000	0.000	0.000	0.000	0.000	0.227	0.240	0.000	0.000	0.000	0.000	0.000	0.000	0.277	0.332	0.345	0.000	0.000	0.285	0.000
R18	0.257	0.206	0.246	0.204	0.231	0.000	0.233	0.223	0.000	0.246	0.000	0.000	0.000	0.000	0.221	0.331	0.310	0.000	0.227	0.261	0.000
R19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.208	0.000	0.000	0.000	0.000	0.000	0.273	0.263	0.000	0.000	0.218	0.000
R20	0.218	0.000	0.210	0.217	0.241	0.000	0.222	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.237	0.255	0.000	0.240	*0.263*	0.000
R21	0.286	0.000	0.287	0.206	0.215	0.000	0.290	0.287	0.000	0.000	0.000	0.000	0.000	0.000	0.220	0.314	0.350	0.000	0.273	0.280	0.238
R26	0.238	0.000	0.235	0.206	0.225	0.000	0.265	0.255	0.000	0.000	0.000	0.000	0.000	0.000	0.232	0.294	0.329	0.000	0.000	0.306	0.000
R27	0.256	0.000	0.243	0.000	0.000	0.000	0.269	0.240	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.291	0.286	0.000	0.241	0.237	0.218

Source: Created by authors

4.2 Impact level analysis

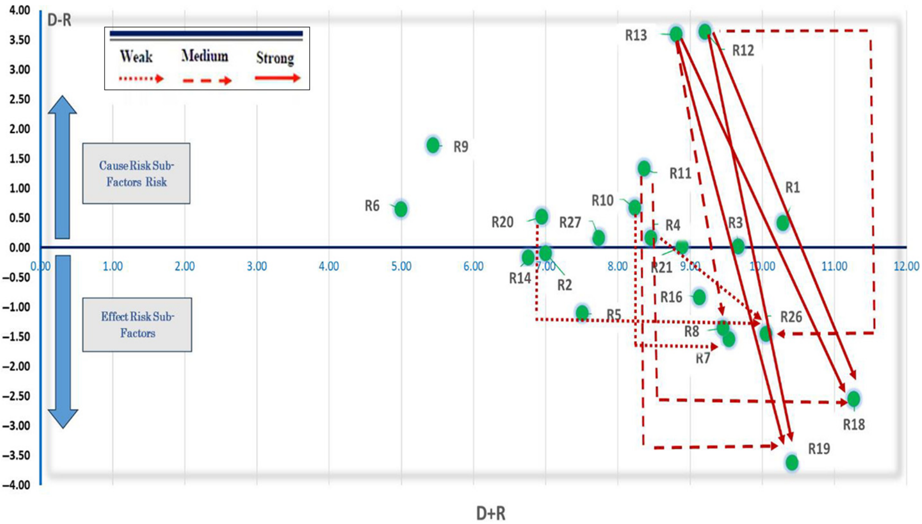
The level of impact can be analysed based on the impact matrix (Table 5). There are three impact levels: weak, medium and robust. The following will discuss the relationship between any sub-risk factors classified as weak, medium and substantial impact, which influence the implementation of SRSC.

Threshold value = 0.202
Minimal: 0.202
Average: 0.275
Higher: 0.391
Maximal: 0.507
The degree of impact:

- Value 0 = no relationship
- The relationship between the variables themselves is ignored
- Weak impact = 0.202–0.275 shown in the orange block
- Medium impact = 0.276–0.391 shown in green block
- Strong impact = 0.392–0.507 shown in yellow block

4.2.1 Weak impact. A sub-risk factor has a weak impact if the relationship value between two sub-risk factors (in the cause category and impact category) ranges between 0.202 and 0.275, marked with a thin dotted line (Figure 4). When looking at the values in the impact matrix in Table 5. Weak impacts occur in the three relationships that have the highest values in sequence, namely:

- the relationship between changes in preferences (R4) (cause category) and damage during storage (R26) (impact category) with a value of 0.272;



Source: Created by authors

Figure 4. Mapping the impact between sub-risk factors in a cause and impact diagram

- the relationship between the use of R10 chemical pesticide fertiliser and low output prices (R7) with a value of 0.267; and
- the relationship between limited knowledge of GAP and GMP (R20) and damage during storage (R26) with a value of 0.263.

4.2.2 Medium effect. A sub-risk factor has a medium impact if the relationship value between two sub-risk factors (in the cause category and impact category) ranges between 0.276 and 0.391, marked with a dotted line (Figure 4). When looking at the values in the impact matrix in Table 4, moderate impacts occur in the four relationships that have the highest values in sequence, namely:

(1) the relationship between rainfall (R13) and high input prices (R8) with a value of 0.391;

(2) the relationship between pests and diseases (R11) and yield loss (R18) with a value of 0.388;

(3) the relationship between flooding (R12) and damage during storage (R26) with a value of 0.388; and

(4) the relationship between pests and diseases (R11) and low quality of results (R19) with a value of 0.386.

4.2.3 Strong effect. A sub-risk factor has a strong impact if the relationship value between two sub-risk factors (in the cause category and impact category) ranges between 0.392 and 0.507, marked with a thick line (Figure 4). When looking at the values in the impact matrix in Table 4. Substantial impacts occur in the four relationships that have the highest values in sequence, namely:

(1) the relationship between flooding (R12) and low quality of results (R19) with a value of 0.507;

(2) the relationship between flooding (R12) and yield loss (R18) with a value of 0.496;

(3) the relationship between rainfall (R13) and low quality of produce (R19) with a value of 0.482; and

(4) the relationship between rainfall (R13) and yield loss (R18) with a value of 0.479.

5. Discussion

Based on the study's results, it is stated that the risk of climate change (flood sub-factor and rainfall sub-factor) is the leading cause category and is also part of the solid and moderate impacts. It affects the entire SRSC system. Moreover, this proves that farmers in the rice supply chain accept this risk when carrying out farming activities, starting from land processing activities, planting, using production inputs, maintenance, harvesting and post-harvesting activities – also remembering that this risk is beyond the limitations of farmers to handle it. Thus, the risk of climate change in rice farming must be a significant concern because it is related to the availability of rice for the population. These findings are consistent with previous research analysing supply chain risks. Natural disasters can directly or indirectly affect almost all other sources of risk, where the relationship is one way, meaning that a natural disaster can lead to other risks (Ghadge *et al.*, 2020; Ramos *et al.*, 2021). The study results in Nigeria also stated that rainfall and humidity, which affect water content, are risks that rice farmers face during the cultivation, harvest and post-harvest processes (Paul and Ifeyinwa, 2016).

Our research also underscores the importance of two critical impacts of climate change that should be of primary concern to farmers: the risk of low grain quality and the risk of yield loss. These are not just abstract risks but tangible threats to production. A study on rice in East Java, Indonesia, further supports these findings, highlighting damage or loss of quality and an uncertain climate as the two highest risk factors. Armed with this knowledge, farmers can better prepare and adapt to these challenges (Rohmah *et al.*, 2015). This is also reinforced by the results of previous research, which shows that farmers often consider production risk to be one of the most important types of risk (Komarek *et al.*, 2020). Thus, the focus on production risks is understandable, considering that productivity in agriculture is closely related to climate. Farmers in Malaysia, Thailand and Vietnam also face the same rice risks, such as weather and climate change, significantly affecting productivity and processing (Anthony Lam *et al.*, 2015a; Firdaus *et al.*, 2020).

In Vietnam, Shrestha *et al.* (2016) also prove that climate change will reduce rice production from 1.29% to 23.05% during winter, while a yield increase of 2.07% to 6.66% is expected in summer. Climate change has become a pressing issue in South Asia, damaging agriculture and threatening food security (Rasul, 2021). The agricultural systems of developing countries are largely dependent on rainfall due to a lack of technological adaptation (Ogallo *et al.*, 2000). This requires farmers to improve technology regarding cultivation and monitoring grain quality (Nga, 2021). The consequences of climate change risks experienced by rice farmers will undoubtedly increase the risk of yield loss and threaten the population's food security. This will impact the supply of harvested dry grain (GKP) and milled dry grain (GKG) needed by rice milling businesses. The milling process does not reach total capacity because the grain supply is insufficient, which causes processing costs to be high. This is what causes many rice milling businesses to stop operating.

Apart from climate change risks, which are included in the cause category, operational risks, namely, limited knowledge of GAP and GMP (Good *et al.*), are also essential to discuss. Even though this sub-risk factor has a weak impact relationship with damage during storage, in reality, in the field, this sub-risk factor occurs most frequently, which is experienced by farmers and other supply chain actors, namely, rice milling businesses. Especially for rice milling businesses, the risk is limited knowledge regarding GMP. This is very natural because different actors in the supply chain will face other dangers. After all, the processes/activities are also different (Singhal *et al.*, 2011).

GMP knowledge possessed by rice milling businesses in Indonesia still needs to be improved; it has been proven that premium-quality rice cannot be produced. Based on information in the field, the quality of the rice produced is still low; more than 20% of the rice is broken and not uniform, and the yield still needs to be higher, namely, 50%–60%. This causes the loss rate to be relatively high. Apart from that, 95% of small-scale rice milling businesses (milling capacity of no more than 1,500 kg of rice per hour) generally do not have dryers, so they cannot maintain the quality of the rice. It is also the case in Myanmar that most rice businesses are still on a small scale and need to expand the size of their operations (Linn and Maenhout, 2019). Not to mention the supply of raw materials, namely, milled dry unhulled rice (GKG), which still needs to meet standards, considering that in the rice milling process, the quality of the rice produced is greatly influenced by the raw materials, the low level of GKG quality will produce rice that breaks easily, among other things, due to technical cultivation factors, tidal paddy field factors, fertility and fertilisation factors, grain drying technique factors and dry grain harvesting (GKP) factors.

However, it is also necessary to explain the results of previous studies that differ from the results of this study, like Wahyuningtyas *et al.* (2021) state that the risks faced by the rice milling industry are price risks, quality risks and grain supply. On the other hand, the risk that is a priority for farmers to manage is disease pests. Also different from the findings of the research, Nga (2021) states that in Vietnam, manufacturing risks, demand risks, logistics risks, information risks and environmental risks are essential risks faced by rice supply chain players, especially those involved in rice export and import activities.

6. Conclusion

6.1 Academic contribution

Academically, this study examines various important insights for academics and professionals involved in determining critical risks that can influence how well SRSC is practised to achieve food security. This study also aims to increase knowledge of a complete list of risk factors and sub-factors derived from the sustainability dimension related to the rice supply chain, sustainability and food security, which have yet to be widely researched. Business ventures and policymakers can use the suggested approach to determine essential risks affecting how well SRSC will be implemented.

The main findings of the study were to (1) provide empirical evidence of the main risks that could make SRSC vulnerable, namely, climate change risks (such as flooding and rainfall) from environmental dimensions, as well as operational risks (such as losses from low-quality results) from process dimensions, despite many previous studies, such as those by Ghadge *et al.* (2020) and Ramos *et al.* (2021) have analysed risk factors in the context of the rice supply chain and shared the same findings, but many previous studies have also produced different findings (Gligor *et al.*, 2018; Hussain *et al.*, 2022; Das *et al.*, 2023). This certainly enriches the review literature and proves that the SRSC risk model resulting from this study makes a theoretical contribution to food security efforts in the developing world, which has never been done before. (2) Develop an MCDM-based framework to discover, rank and reveal relationships between SRSC risks from economic, social, environmental and operational aspects through the joint integration of Fuzzy-Dematel techniques and Pareto analysis. However, many previous considerations related to risks using this integration are specific to SRSC risks, even more so in food security efforts for developing countries that have never been undertaken. The study is, therefore, the only initial initiative to test the feasibility of SRSC implementation in a developing country context. Based on the above, this study contributed significantly to completing the identified gaps and proving the theoretical framework (Fuzzy-Dematel technique and Pareto analysis) to identify and analyse risks in the context of the rice supply chain in food security efforts in developing countries.

6.2 Managerial contribution

This study was conducted to make SRSC practices more effective in the rice supply chain to reach food security. The risk dimensions, risk factors and significant sub-risk factors of SRSC that are evaluated and assessed will help supply chain actors in developing countries improve their performance in providing rice food for their populations. The findings also show that risk factors have a weak, medium and robust impact relationship that benefits stakeholders. It helps them to understand which risk factors influence the rice supply chain. Therefore, it will result in sustainable food for people in developing countries, which will help both physically and economically. Preceding the process, the sub-factors discovered be grouped according to their nature, either as a cause or an effect of the food security level.

Based on the study findings, the sub-risk factors focus on the risks farmers and rice milling businesses image. Then, the impact matrix between sub-risk factors shows that flooding and rainfall (considered as the cause) strongly correlate with yield loss and low yield quality (considered as the impact). This shows that the environmental dimension, especially the risk of climate change (included in the causal category), is an essential factor that needs to be considered, especially for farmers, so that the rice supply chain can continue. Comprehensively, three sub-risk factors in the SRSC relied as a cause of certain conditions. Those three are grouped as "cause group", namely, (1) flood, (2) rainfall (climate change risk; and environmental dimension) and (3) limited knowledge of GAP and GMP. These risks must be managed to minimise the risk of yield loss and low-quality results. In this way, food security will be ensured. Levelled by importance, the "cause group" shall be the main focus as it influences the "impact group".

The following is an action plan that can be carried out in an integrated manner to formulate an effective strategy for SRSC to minimise the risks faced by farmers and the rice milling industry. Firstly, drought-resistant rice varieties should be planted, groundwater use should be increased, other crops should be planted, access to climate information should be provided and agricultural subsidies should be provided. Different techniques may reduce the chance of crop loss, including increasing fertilisation initiatives and planting high-temperature types. Similar suggestions were also offered by Bairagi *et al.* (2020), as it was carried out in Cambodia. Secondly, adjust planting time, amount and timing of fertiliser application and irrigation water delivery). This recommendation was given by Boonwichai *et al.* (2019) which was carried out in Thailand. Thirdly, other approaches include building a second reservoir for the drainage system, switching to rice types with shorter growing cycles, planting improved rice varieties, changing planting and harvest times and planting rice varieties resistant to climate change. Fourthly, vocational training courses related to GMP and GAP for farmers and rice milling businesses should be increased. Fifthly, for the rice milling industry, developing a rice milling model at the research site should consider the number and capacity of RMU machines, considering that it is not a rice centre area. RMU machine capacity leads to small and medium capacities built at several grain production points with adequate machine configuration/equipment to produce rice at a premium quality level.

6.3 Limitation and future scope

This study implements effective initiatives in managing risks in SRSC to achieve food security, especially in developing countries. Rice supply chain actors must ensure rice availability, accelerate productivity and help solve the current rice food problem. In this case, risks and uncertainties need to be considered so that losses can be minimised. For this reason, it is essential to identify, evaluate and determine the risks that influence the adoption of SRSC in developing countries. This study suggests an integration approach that combines Pareto and Fuzzy-Dematel analysis with other techniques. This study identifies four sustainability dimensions of rice supply chain risk, acknowledging that it may be incomplete. Future research could expand these dimensions. In addition, as technology, government legislation and administrative procedures develop, risk dimensions, risk factors and sub-factors will also vary. Therefore, to verify the validity and relevance of the study, it may be necessary to repeat it in about five years.

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Appendix 1. Primary questionnaire

The experts were asked the following questions to allow us to identify the relevant risk factors.

- What is your organisation type?
- What are your areas of expertise?
- What is your work experience?
- What is your education?

Give your valuable opinion on the relevant factors that will help rice supply chain players be sustainable in developing countries to achieve resilience.

Stage I. Identify risk factors for developing countries' sustainable rice supply chains to achieve food security

Table A1. Please check the relevance of the factors. We ask you to add or remove any factors if you feel that way

No.	Risk sub-factors	Is it relevant? (yes/no)
1	Limited production inputs	
2	Limited superior seeds/lack of high-yield seeds	
3	Limited agricultural tools and machinery	
4	Distortion of information	
5	Inconsistency between demand and forecast	
6	Consumer preference for rice changes throughout the year	
7	Changes in the need for healthy and safe food	
8	Uncertain input prices	
9	Low output prices	
10	Market uncertainty in terms of quality and quantity	
11	Limitations of potential market opportunities	
12	High input prices	
13	Excessive heavy metals in the soil (use of fertilisers, pesticides and other chemicals)	
14	Pests and diseases of crops	
15	Gas emissions greenhouse	
16	Contamination related to food safety (bleaching and rice husks)	
17	Flood	
18	Extreme winds (wind chill)	
19	Rainfall surplus/deficit	
20	Extreme drought	
21	Emergence of disturbing situations such as pandemics, earthquakes and wars	
22	Uncertain trade and market policies	
23	Unpredictable policies and regulations	
24	Uncertain monetary, fiscal and tax policies	
25	Lack of skills and experience in production	
26	The limited institutional role of cooperatives, extension workers, farming groups, etc	
27	Health and safety equipment of workers	
28	Limited financial support	
29	Loss of yield	
30	Low mill capacity	
31	Low production quality	
32	Uncertain interest rate and exchange rate policies	
33	Slow return on assets	
34	Slow return on assets financial support (agricultural contracts and credit support)	
35	Delay in accessing financial support	
36	Low logistic performance	
37	Limited stock-level information	
38	Limited storage/warehousing	
39	*Poor packaging (limitation of the application of green packing)*	
40	Limited infrastructure and service (electricity, water, etc.)	
41	Poor road conditions	
42	Emission gas during delivery	
43	Damage in shipping	
Please add risk factors if you think they are irrelevant or not already on the list		
1	………………………	
2	…………………………	
3	…………………………	
4	……………………………	
5	……………………………….	

Source: Created by authors

Stage II. Selecting the crucial risk factors for sustainable rice supply chains in developing countries is important to achieve food security

Table A2. Please give ratings between 1 and 5 to the following factors, where 1 is "insignificant", 5 is "very negligible" and the rest in between

Code	Risk sub-factors	Give a rating (1–5)
R1	Limited production inputs	
R2	Limited agricultural tools and machinery	
R3	Low supplier quality	
R4	Inconsistency between demand and forecast	
R5	Changes in the need for healthy and safe food	
R6	Input price uncertainty	
R7	Low output prices	
R8	High input prices	
R9	Limited irrigation	
R10	Excessive heavy metals in the soil (use of fertilisers, pesticides and other chemicals)	
R11	Plant pests and diseases	
R12	Flood	
R13	Rainfall surplus/deficit	
R14	Uncertain trade and market policies	
R15	Unpredictable policies and regulations	
R16	Limited institutional roles include co-operatives, extension workers, farmer groups, etc	
R17	Limited financial support	
R18	Loss of yield	
R19	Low quality of production	
R20	Limited knowledge of good agriculture practice (GAP) and good manufacturing process (GMP)	
R21	Uncertainty of financial support (agricultural contracts and credit support)	
R22	Delay in accessing financial support	
R23	Limited stock-level information	
R24	Limited storage/warehousing	
R25	*Poor packaging (limitation of the application of green packing)*	
R26	Damage during storage	
R27	Poor road conditions	
R28	Damage in shipping	

Source: Created by authors

Stage III. Selecting the direct relationship of one risk sub-factor to another sub-factor using a 0–4 scale where 0: no influence, 1: meagre influence, 2: influence, 3: strong influence and 4: powerful influence

Table A3. Please choose the correct scale to declare the relationship between risk sub-factors

Risk SF	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R16	R18	R19	R20	R25	R26	R27
R1																					
R2																					
R3																					
R4																					
R5																					
R6																					
R7																					
R8																					
R9																					
R10																					
R11																					
R12																					
R13																					
R14																					
R16																					
R18																					
R19																					
R20																					
R25																					
R26																					
R27																					

Source: Created by authors

Appendix 2. Respondent characteristics

Table A4. Characteristics of experts who participated in this research

Total expert	Expert characteristics		No. of experts	%
12	Organisation type	1. Provincial research and development agency	1	8.33
		2. Provincial food crops and horticulture service	1	8.33
		3. Provincial food security agency	2	16.67
		4. District food security and agriculture service	4	33.33
		5. Faculty of agriculture	2	16.67
		6. Business/private	2	16.67
	Areas of expertise	1. Availability of food and resources	1	8.33
		2. Food distribution and reserves	1	8.33
		3. Rural development	4	33.33
		4. Agricultural economics	2	16.67
		5. Food technology	1	8.33
		6. Farming	1	8.33
		7. Milling industry	1	8.33
		8. Marketing	1	8.33
	Work experience	1. 5–10 years	4	33.33
		2. 11–20 years	4	33.33
		3. >20 years	4	33.33
	Education	4. High school	2	16.67
		5. Graduate	4	33.33
		6. Postgraduate	4	33.33
		7. PhD	2	16.67

Source: Created by authors

Appendix 3. List of risk sub-factors

Table A5. Sub-risk factors used for Fuzzy-Dematel analysis

Code	Risk sub-factors	F-Dematel
R1	Limited production inputs	√
R2	Limited agricultural tools and machinery	√
R3	Quality of input suppliers	√
R4	Preference changes	√
R5	Inconsistency between demand and forecast	√
R6	Uncertain input prices	√
R7	Low output prices	√
R8	High input prices	√
R9	Limited availability of water/irrigation	√
R10	Use of chemical pesticide fertilisers	√
R11	Plant pests and diseases	√
R12	Flood	√
R13	Rainfall (surplus/deficit)	√
R14	Uncertain trade and market policies	√
R15	Unpredictable policies and regulations	**x**
R16	Limited role of cooperative institutions, extension workers, farmer groups, etc.	√
R17	Limited financial support	**x**
R18	Loss of results	√
R19	Low production quality	√
R20	Limited knowledge of good agriculture practice (GAP) and good manufacturing process (GMP)	√
R21	Uncertainty of financial support (contract farming, credit support and insurance)	√
R22	Delays in aid programmes	**x**
R23	Limited stock-level information	**x**
R24	Limited storage/warehousing	**x**
R25	Poor packaging (limitations in the application of green packing)	**x**
R26	Damage during storage	√
R27	Poor road conditions	√
R28	Damage in shipping	**x**

Notes: x: risk factors were removed after Pareto analysis; √: finalisation of risk factors for Fuzzy-Dematel analysis

Source: Created by authors

Appendix 4. Stages of the Fuzzy-Dematel method

The following are the steps for carrying out the fuzzy-Dematel method.

(1) *Step 1*: All 12 experts were asked individually to evaluate the direct relationship of one risk sub-factor to another using the 0–4 scale presented in Table A6. Then, the result is the initial direction relation matrix (Table A7).

Table A6. Fuzzy linguistic scale

Scale	Abbreviation	Linguistic preference	Corresponding TFNs
0	NI	No influence	(0.0; 0.1; 0.3)
1	VL	Very low influence	(0.1; 0.3; 0.5)
2	I	Influence	(0.3; 0.5; 0.7)
3	HI	High influence	(0.5; 0.7; 0.9)
4	VH	Very high influence	(0.7; 0.9; 1.0)

Source: Created by authors

Let $\omega_{ij}^{\sim k} = \left(a_{1ij}^k, a_{2ij}^k, a_{3ij}^k\right)$, This means the level of sub-risk factor i that influences sub-risk factor j and the fuzzy assessment of several k experts (k = 1; 2; [...]; k). because the fuzzy number formula is incompatible with matrix operations, it is necessary to convert/transform from a fuzzy number to a crisp one. For this reason, the Defuzzification process needs to be implemented. Then, proceed with aggregation as a crisp value. Here are the next steps.

(2) *Step 2*: change the linguistic variables into corresponding TFNs

The linguistic variables are changed from the initial direction relation matrix into the corresponding TFNs.

(3) *Step 3*: normalising these TFNs

These initial fuzzy direct relationship matrices are converted into normalised fuzzy direct relations matrices using the equation (D1). The normalised fuzzy direct relations matrix from 1 expert is presented in Table A7:

$$\begin{aligned} xa_{1ij}^k &= a_{1ij}^k - \min a_{1ij}^k / \Delta_{min}^{max} \\ xa_{2ij}^k &= a_{2ij}^k - \min a_{2ij}^k / \Delta_{min}^{max} \\ xa_{3ij}^k &= a_{3ij}^k - \min a_{3ij}^k / \Delta_{min}^{max} \end{aligned} \quad \text{(D1)}$$

Where $\Delta_{min}^{max} = max\ r_{ij}^n - \min l_{ij}^n$

(4) *Step 4*: calculate the right (rs) and left (ls) normalised values:

$$\begin{aligned} xls_{ij}^k &= xa_{2ij}^k / \left(1 + xa_{2ij}^k - xa_{1ij}^k\right) \\ xls_{ij}^k &= xa_{2ij}^k / \left(1 + xa_{2ij}^k - xa_{1ij}^k\right) \end{aligned} \quad \text{(D2)}$$

(5) *Step 5*: calculate the crisp values $\left(x_{ij}^k\right)$:

Table A7. Initial direction relation matrix for risk sub-factors for Expert 1

Risk SF	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R16	R18	R19	R20	R21	R26	R27
R1	1	NI	HI	LI	NI	NI	VH	VH	LI	VH	VL	NI	NI	NI	HI	NI	NI	NI	HI	LI	VH
R2	NI	1	NI	VL	NI	NI	NI	HI	VH	HI	LI	NI	NI	NI	VH	NI	NI	NI	NI	LI	NI
R3	VH	NI	1	NI	NI	NI	VH	VH	VH	VH	LI	NI	NI	NI	HI	NI	NI	NI	HI	HI	HI
R4	HI	HI	HI	1	HI	NI	HI	HI	HI	HI	HI	NI	NI	VL	HI	NI	VL	NI	VL	LI	VL
R5	LI	NI	NI	HI	1	NI	NI	NI	NI	LI	NI	NI	NI	LI	HI	NI	HI	LI	LI	LI	LI
R6	NI	NI	NI	VL	LI	1	LI	VH	VH	VH	VL	NI	NI	NI	LI	NI	NI	NI	NI	VH	NI
R7	VH	LI	LI	VL	LI	NI	1	VH	VH	VH	LI	NI	NI	NI	LI	NI	NI	NI	LI	LI	LI
R8	LI	NI	NI	VL	LI	NI	VH	1	VH	VH	NI	NI	NI	NI	HI	NI	NI	NI	HI	VH	HI
R9	LI	NI	NI	LI	VL	NI	NI	NI	1	HI	NI	NI	NI	NI	VL	NI	NI	LI	VL	LI	VL
R10	LI	NI	NI	LI	LI	NI	HI	VL	VH	1	NI	NI	NI	NI	VH	NI	HI	LI	VL	VH	VL
R11	VH	VH	NI	HI	VL	LI	VH	VH	VH	VH	1	NI	NI	VH	VH	NI	VH	VL	NI	VH	NI
R12	LI	NI	NI	LI	LI	NI	VH	VH	VH	VH	NI	1	VL	NI	HI	LI	VL	VL	LI	LI	LI
R13	VL	NI	NI	VL	NI	VH	VH	VH	VH	VH	NI	VH	1	NI	LI	VL	LI	VL	VL	VL	VL
R14	NI	NI	NI	NI	LI	NI	NI	NI	NI	HI	NI	NI	NI	1	LI	NI	LI	NI	NI	HI	NI
R16	LI	NI	LI	HI	HI	NI	NI	NI	NI	VH	NI	NI	NI	VL	1	NI	HI	VL	VL	VH	NI
R18	LI	LI	VL	VL	LI	NI	VL	NI	VL	VL	NI	NI	NI	NI	NI	1	HI	VL	VL	LI	VL
R19	HI	NI	LI	LI	LI	NI	NI	NI	NI	LI	NI	NI	NI	NI	NI	NI	1	VL	VL	LI	VL
R20	VH	VL	HI	HI	HI	NI	LI	VL	VL	VL	VL	NI	NI	VL	VL	NI	VL	1	HI	HI	HI
R21	VH	VL	VH	HI	LI	NI	VH	VH	VH	VH	VL	NI	NI	VL	VL	NI	VL	VL	1	HI	VH
R26	VH	HI	LI	VL	LI	NI	VH	VH	VH	VH	VL	NI	NI	HI	HI	NI	HI	LI	VL	1	VL
R27	VH	HI	VH	VH	VH	NI	VH	VH	VH	VH	LI	NI	NI	LI	LI	NI	LI	LI	VH	HI	1

Note: Provided by one of 12 experts
Source: Created by authors

$$x_{ij}^{k} = \left[xls_{ij}^{k}\left(1 - xls_{ij}^{k}\right) + xrs_{ij}^{k} \times xrs_{ij}^{n}\right] / \left(1 - xls_{ij}^{k} + xrs_{ij}^{k}\right) \quad \text{(D3)}$$

(6) *Step 6*: produce the total normalised crisp values:

$$\omega_{ij}^{\sim k} = \min a_{ij}^{n} + x_{ij}^{n} \Delta_{min}^{max} \quad \text{(D4)}$$

(7) *Step 7*: aggregating the normalised crisp values from all experts using equation (D5):

$$\omega_{ij}^{\sim k} = 1/\mathrm{k}\left(\omega_{ij}^{\sim 1} + \omega_{ij}^{\sim 2} + \ldots + \omega_{ij}^{\sim k}\right) \quad \text{(D5)}$$

(8) *Step 8*: produces the normalised direct matrix (O), which is obtained through the equation (C7):

$$\mathrm{k} = \frac{1}{\underset{1 \le i \le n}{max} \sum_{j=1}^{n} aij} \quad \text{(D6)}$$

$$\mathrm{O} = \mathrm{k} \times \mathrm{A} \quad \text{(D7)}$$

(9) *Step 9*: establishing an identity matrix (I)

(10) *Step 10*: subtracting the identity matrix (I) from the normalised direct matrix (O) and calculating the inverse

(11) *Step 11*: build the total relation matrix (T) by multiplying the (I-O) − 1 matrix and (O) matrix using the equation (D8):

$$\mathrm{T} = \mathrm{O}(\mathrm{I{-}O})^{-1} \quad \text{(D8)}$$

where I = identity matrix; T = total relation matrix,

$$\mathrm{T} = [\mathrm{t_{ij}}]_{\mathrm{nxn}} \quad \mathrm{i, j = = 1, 2, \ldots n} \quad \text{(D9)}$$

(12) *Step 12*: calculate D and R using equations (D10) and (D11)

Accumulating the horizontal values (the sum of the rows) produces the (D), and accumulating the vertical values (the sum of the columns) produces the (R) in the total relation matrix (T);

$$D = \left[\sum_{i=1}^{n} t_{ij}\right]_{\mathrm{n} \times 1} = [t_{ij}]_{n \times 1} \quad \text{(D10)}$$

$$R = \left[\sum_{j=1}^{n} t_{ij}\right]_{n \times 1} = [t_{ij}]_{n \times 1} \quad \text{(D11)}$$

(13) *Step 13*: calculate (D + R) and (D − R) to map cause categories and impact categories

(14) *Step 14*: visual analysis based on cause and impact category diagrams and plotting arrows indicating effects.

(15) *Step 15*: perform the following actions:

- Find the threshold value (TV) of the total relation matrix (T). TV is obtained from the overall average value of T.
- Uses threshold values to identify impact categories between sub-risk factors. If the value in T $\geq$ the threshold value, then it automatically indicates the existence of the effect and vice versa.
- Sub-risk factors that have a relationship will then determine the level of impact by looking for the minimum, average, higher and maximum values. The impact levels consist of weak, medium and robust impacts.

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