The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1985-9899.htm

A risk assessment framework using neutrosophic theory for the halal supply chain under an uncertain environment

Shahbaz Khan
GLA University, Mathura, India
Abid Haleem
Jamia Millia Islamia, New Delhi, India, and
Mohd Imran Khan
Lovely Professional University, Phagwara, India

Received 22 December 2022
Revised 6 May 2023
17 June 2023
Accepted 19 June 2023

Abstract

Purpose – The complex network structure causes several disruptions in the supply chain that make risk management essential for supply chain management including halal supply chain (HSM). During risk management, several challenges are associated with the risk assessment phase, such as incomplete and uncertain information about the system. To cater this, the authors propose a risk assessment framework that addresses the issues of uncertainty using neutrosophic theory and demonstrated the applicability of the proposed framework through the case of halal supply chain management (HSCM).

Design/methodology/approach – The proposed framework is using the capabilities of the neutrosophic number which can handle uncertain, vague and incomplete information. Initially, the risk related to the HSC is identified through a literature review and expert's input. Further, the probability and impact of each HSM-related risk are assessed using experts' input through linguistic terms. These linguistic values are transformed into single-value trapezoidal neutrosophic numbers (SVTNNs). Finally, the severity of each HSM-related risk is determined through the multiplication of the probability and impact of each risk and prioritised the risks based on their severity.

Findings – A comprehensive risk assessment framework is developed that could be used under uncertainty. Initially, 16 risks are identified related to the HSM. Further, the identified risks are prioritised using the severity of the risks. The high-priority risk is “raw material status”, “raw material wholesomeness” and “origin of raw material” while “information integrity” and “people integrity” are low-priority risks.

Practical implications – HSM risk can be effectively assessed through the proposed framework. The proposed framework applied neutrosophic numbers to represent real-life situations, and it could be used for other supply chains as well.

Originality/value – The proposed method is effectively addressing the issue of linguistic subjectivity, inconsistent information and uncertainty in the expert's opinion. A case study of the HSC is adopted to illustrate the efficiency and applicability of the proposed risk framework.

Keywords Halal supply chain, Neutrosophic theory, Risk, Risk assessment, Single value trapezoidal neutrosophic numbers

Paper type Research paper

Arab Gulf Journal of Scientific Research
Emerald Publishing Limited
e-ISSN: 2536-0051
p-ISSN: 1985-9899
DOI 10.1108/AGJSR-12-2022-0312

1. Introduction

Risk management has become a major research area in the field of supply chain management over the last few years (Shan, Xiong, & Zhang, 2023). Academic scholars and professionals have given greater consideration to risk management in supply chains as a means of reducing vulnerability (Liu, Zhou, & Gao, 2022; Balfaqih, Nopiah, Saibani, & Al-Nory, 2016; Behzadi, O'Sullivan, Olsen, & Zhang, 2018). The primary reason behind this attention towards risk management could be increasing risk events such as natural disasters, economic crises, market fluctuations, increased outsourcing and offshoring, pandemic and wars (Gebhardt, Spieske, Kopyto, & Birkel, 2022; Wiengarten, Humphreys, Gimenez, & McIvor, 2016). Due to the major emphasis of the industries on improving the efficiency of the supply chain, the current global supply chain is becoming more vulnerable and fragile to disruptions (Song, Ma, Zhao, & Zhang, 2022).

The generic risk management framework is constituted of four stages, and the risk assessment phase is considered a vital phase of risk management. Risk assessment is the process of risk quantification to mitigate these risks as per their severity (Khan, Haleem, & Khan, 2022; Shankar, Choudhary, & Jharkharia, 2018). The conventional risk assessment model uses crisp values in their method, and these crisp values are not efficient for risk evaluation (Tian, Chen, & Wu, 2022). The risk assessment procedure assesses risks before their occurrence. In other words, these risk estimations are related to the future state. In this regard, it is very difficult to give a direct and correct numerical value in a crisp manner. To overcome this issue, advanced methods use linguistic/subjective data for assessment of risks, such as "low, medium, high, likely occur", etc. These linguistic variables bring linguistic subjectivity to their assessment (Singh *et al.*, 2022). Linguistic subjectivity refers to the idea that language use is influenced by personal experiences, beliefs, values and emotions (Singh *et al.*, 2023. It means that language is not neutral or objective, but rather shaped by the person's perspective. In order to address linguistic subjectivity, fuzzy theories are used that can easily transform and modelled (Muneeb, Asim, & Adhami, 2019; Dong & Cooper, 2016). It is also important to note that the expert's input is subject to some additional complexities, including fuzziness, incomplete and inconsistent information (Hashmi, Jalil, & Javaid, 2021). These issues are not addressed concurrently by the fuzzy set theories including their different variants such as intuitionistic fuzzy theory (Hashmi, Aqib Jalil, & Javaid, 2022). On the other hand, these issues concurrently address the neutrosophic numbers by transforming the linguistic input (Simić, Milovanović, Pantelić, Pamučar, & Tirkolaee, 2023). Three membership elements in neutrosophic numbers distinguish them from fuzzy and intuitionistic fuzzy numbers (IFNs): truth, indeterminacy, and falsity (Smarandache, 1998). Hence, it could resolve the fuzziness, incomplete and inconsistence information, better than fuzzy and IFNs (Abdel-Basset, Gunasekaran, Mohamed, & Smarandache, 2018).

To overcome the limitation to handle the fuzziness and incomplete and inconsistent information of the conventional risk assessment approach, the neutrosophic numbers can be utilised in the risk assessment. Therefore, this study purposes a novel risk assessment method to assess the risk using the neutrosophic numbers. In this method, the probability of the risk occurrence and impact obtained from the experts are transformed into single-value trapezoidal neutrosophic numbers (SVTNNs). Based on the probability of occurrence and their impact, the severity of the risk is determined. As a result of the proposed method, it will be possible to make precise decisions and efficiently assess risks. In this study, a case study of halal supply chain management (HSCM) is used to illustrate the proposed methodology. The primary objectives of the research are as follows:

(1) To propose a risk assessment framework in the uncertain environment.

(2) To illustrate the proposed methodology with an HSCM.

(3) To recommend the risk mitigation for the HSCM.

The above-mentioned research objectives are fulfilled through the development of the risk assessment framework and validated with the case of HSCM. This paper illustrates the proposed risk assessment framework by identifying the risks associated with the halal supply chain (HSC) based on the literature review and validating with the opinions of experts. After that, the neutrosophic numbers are used to quantify and rank the risks related to the HSC with the consultation of domain experts. Further, some useful suggestions are provided to mitigate the potential risks.

The remaining paper is arranged as follows: Section 2 literature review of this study; Section 3 illustrates the proposed framwork for the risk assessment; Section 4 provides a case study to demonstrate the proposed risk assessment framework; Section 5 provides an overview of the results of the study, Section 6 provides an overview of the results of the study, and Section 7 discusses the implications of the research.

2. Literature review

This section provides a brief review of the concept of halal, risk assessment model and the application of the neutrosophic set theory in multi criteria decision making (MCDM) problems.

2.1 Halal supply chain and risk management

Halal is an Arabic word that means permissible, acceptable and lawful, and the crux of it is that all consumables and foods are considered halal, except where specific restrictions are imposed by Shariah. Therefore, in Islamic law (Shari'ah), everything that is permissible is halal (Khan, Haleem, & Khan, 2018; Ab Talib and Zulfakar, 2023). Essentially, Halal promotes people's ability to maintain cleanliness in all aspects of their lives through their choice of products and services. In addition to being safe for consumption, halal products are produced in a clean environment and have become the standard for quality (Khan, Haleem, Ngah, & Khan, 2023). In order to fulfil the demand and facilitate the flow of halal products, the concept of HSCM is emerging. As part of supply chain management, product flows, capital flows and information flows are also managed. The HSC must meet the Shariah requirements to ensure halal integrity for consumers (Ali, Tan, & Ismail, 2017).

The HSC refers to the flow of products from origin to consumption in which halal and toyyib conditions are taken into account along the supply chain (Omar and Jaafar, 2011). HSCM is responsible for maintaining the halal status throughout the supply chain by ensuring the integrity of halal through certifications (Amer, 2023). To maintain halal integrity up to the point of consumption, there are numerous uncertainties present. The HSC is the process of managing halal products from different suppliers to a wide variety of buyers and consumers, involving several different parties located at different places (Zulfakar, Anuar, & Talib, 2014). As halal food products possess the credence quality attribute, it is difficult for the consumer to verify their integrity even after consumption. Therefore, risk management becomes an essential part of HSCM to maintain the halalness of the product up to consumption. Risk management has four primary stages that include identification, assessment, mitigation and control (Khan *et al.*, 2023). Risk identification deals with the potential uncertainty/threats that breach the halal integrity of the product. The risk assessment phase is used for quantifying or prioritising the risks (Khan, Khan, Haleem, & Jami, 2019). Risk mitigation stage focuses on the identification and development of strategies for reducing the risk that is identified in the risk identification phase. Further, risk control deals with the deployment of risk mitigation strategies. Through these four steps, risk management could be done in any supply chain including the HSC.

2.2 Risk assessment model

A number of organisations are advancing their supply chains to the global level to reduce their costs. As a result, such organizations experience new risks due to the possibility that their supply chain could be impacted by political instability, emergencies and natural disasters occurring on the other side of the globe (Abdalkrim and Guizani, 2022). Outsourcing and subcontracting become a necessity of the global supply chain, which leads to increased vulnerability in the supply chain (Javaid & Siddiqui, 2018). Supply chain management becomes more complex due to the tendency to outsource activities, resulting in a longer supply chain and a greater number of variables and interactions to analyse (Cheng, Guo, Li, & Yu, 2022; Anis, Iqbal, Nazir, & Khalid, 2022). In this complex scenario, risk management is challenging for supply chain management.

Among the four stages of risk management, risk assessment is a crucial stage because it has many complexities due to the involvement of several preconceptions (Heckmann, Comes, & Nickel, 2015). Several approaches have been applied for risk assessment such as failure effect mode analysis (Giannakis & Papadopoulos, 2016), interpretive structural modelling (Chand, Raj, & Shankar, 2015), multi-criteria decision-making (Mangla, Kumar, & Barua, 2015; Lin, Li, Xu, Liu, & Liu, 2018) and Bayesian modelling (Qazi, Quigley, Dickson, & Ekici, 2017). These approaches are integrated with the intuitionistic fuzzy set (IFS) theory (Shankar *et al.*, 2018) to enhance the effectiveness of the evaluation. As most of the risks related to the supply chain are qualitative, it is possible to analyse them using the opinion of the experts. Due to the subjective and imprecise inputs provided by these experts (Javaid *et al.*, 2022), it became more difficult to assess the risks precisely. The expert's input is affected by three major complexities, including vagueness, inconsistent information, and uncertainty. However, these approaches are not handled by three major issues simultaneously. Hence, this study tries to develop a risk assessment approach which can handle these three issues simultaneously. In this study, we propose a novel risk assessment approach using the neutrosophic set theory to cater for the issue of vagueness, subjectivity and incomplete information simultaneously.

2.3 Application of neutrosophic set theory

Neutrosophic numbers are a type of mathematical concept that extends traditional real numbers to include a degree of indeterminacy or neutrality. It is part of neutrosophic theory which seeks to explore the interplay between truth, falsehood and indeterminacy. Neutrosophic numbers can be used in several fields, such as decision-making, expert systems and artificial intelligence, where indeterminacy and uncertainty play a significant role. They offer a way to represent complex, uncertain and contradictory information in a more nuanced and flexible way. Neutosophic set theory has been applied to a variety of problems in the literature, including the solution of linear programming problems (Abdel-Basset *et al.*, 2018), quantifying risks in the supply chain (Abdel-Basset *et al.*, 2018); group decision-making (Abdel-Basset, Mohamed, Hussien, & Sangaiah, 2017); consumers' motivations assessment (Vafadarnikjoo, Mishra, Govindan, & Chalvatzis, 2018) and many more. Additionally, neutrosophic set theory is integrated with the MCDM techniques to improve the effectiveness of the techniques. Neutrosophic numbers have been integrated with the technique for order preference by similarity to ideal solution (TOPSIS) (Biswas, Pramanik, & Giri, 2015); decision-making trial and evaluation laboratory (DEMATEL) (Awang, Ghani, Abdullah, & Ahmad, 2018); analytical hierarchy process (AHP) (Abdel-Basset *et al.*, 2018) and Delphi (Vafadarnikjoo *et al.*, 2018). These studies show the effectiveness of the neutrosophic numbers decision-making problem and their potential to deal with uncertainty. However, the adoption of the neutrosophic set theory is not explored in the domain of the HSC. Therefore, this study explores the application of neutrosophic numbers to deal with the risk assessment in the HSC by considering the halal integrity risks.

2.4 Neutrosophic set theory

The neutrosophic set theory was developed by Smarandache (1998); it is a generalisation of fuzzy set theory (FST) and intuitionistic fuzzy set (IFS) (Smarandache, 1998). The FST and IFS have only one degree of membership and two degrees of membership respectively while the neutrosophic set has three degrees of membership (Wang, Smarandache, Zhang, & Sunderraman, 2010; Salama, Broumi, & Smarandache, 2014). A neutrosophic number is represented as (TP, IP and FP), where 'TP' represents the degree of truth, 'IP' represents the degree of indeterminacy and "FP" represents the degree of falsity. The sum of these three values is not necessarily equal to one, as is the case with probabilities. The values of 'TP', 'IP' and 'FP' can range from 0 to 1, with $TP + IP + FP <= 1$. As a result, the neutrosophic theory is capable of representing vague or uncertain information more effectively than FST in practical applications.

3. Proposed framework for the risk assessment of HSC

The risk assessment framework contains the using five steps. The proposed framework is shown in Figure 1. Further, each step is explained as follows:

Step 1: *Risks identification*: Several risks associated with the HSCM are identified by systematic literature reviews, Delphi, Prisma, focus groups, expert input and sometimes their combination.

Step 2: *Experts' input using neutrosophic number*: Experts assign probabilities (P) and impacts (I) to identified risks based on the linguistic scale as Table 1. The probability and impact of the linguistic assessment are converted into equivalent SVTNNs.

Step 3: *Calculate the severity of the risk*: The severity of the risk is the multiplication of the probability and impact of the risk and is shown as:

$$S = P \otimes I \tag{1}$$

Here, the probability and impact are in SVTNN, so these variables are multiplied using the neutrosophic operations. The resultant severity is determined as per equation (2).

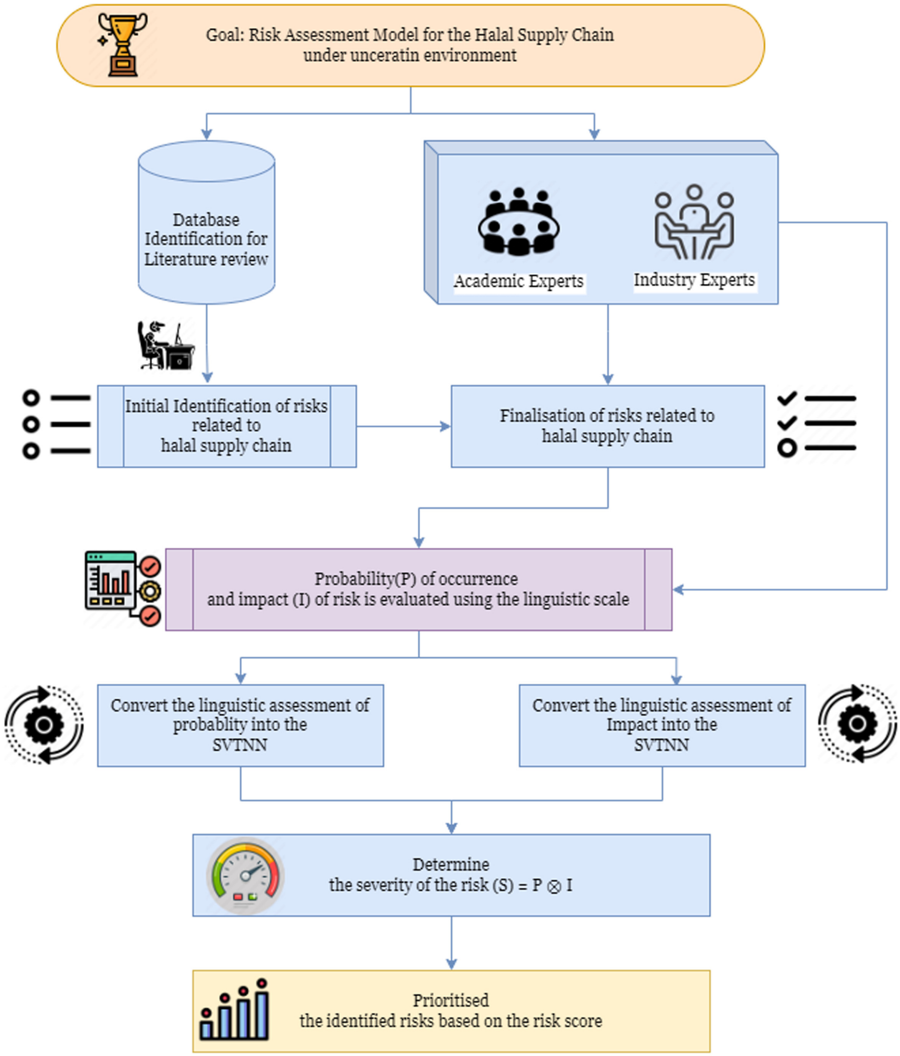
$$S = \left\langle \left(P_1 I_1, P_2 I_2, P_3 I_3, P_4 I_4;\ \alpha_{\tilde{P}} {}^{\wedge} \alpha_{\tilde{I}}, \theta_{\tilde{P}} {}^{\vee} \theta_{\tilde{I}}, \beta_{\tilde{P}} {}^{\vee} \beta_{\tilde{I}}\right\rangle \tag{2}$$

Step 4: *Aggregation of the experts' risk assessments* The severities of the identified risks are aggregated using the following expression.

$$\text{Average}\left(\tilde{p}^1, \tilde{p}^2, \ldots.\tilde{p}^n\right) = \frac{1}{n}\sum_i^n \tilde{p}^i$$
$$= \left\langle \frac{1}{n}\left(\tilde{s}_1^1 + \tilde{s}_1^2 + \ldots + \tilde{s}_1^n\right), \frac{1}{n}\left(\tilde{s}_2^1 + \tilde{s}_2^2 + \ldots + \tilde{s}_2^n\right), \frac{1}{n}\left(\tilde{s}_3^1 + \tilde{s}_3^2 + \ldots + \tilde{s}_3^n\right), \right.$$
$$\left. \frac{1}{n}\left(\tilde{s}_4^1 + \tilde{s}_4^2 + \ldots + \tilde{s}_4^n\right);\ \alpha_{\tilde{s}^1} {}^{\wedge} \alpha_{\tilde{s}^2} {}^{\wedge} \ldots {}^{\wedge} \alpha_{\tilde{s}^n}, \theta_{\tilde{s}^1} {}^{\vee} \theta_{\tilde{s}^2} {}^{\vee} \ldots {}^{\vee} \theta_{\tilde{s}^n}, \beta_{\tilde{s}^1} {}^{\vee} \beta_{\tilde{s}^2} {}^{\vee} \ldots {}^{\vee} \beta_{\tilde{s}^n} \right\rangle \tag{3}$$

where, $\tilde{s}_1^i$ is the severity (of the first neutrosophic number) of risk provided by the ith expert.

n is the total number of experts.



Source(s): Authors' own work

Figure 1.
A proposed framework for risk assessment

Step 5: *Prioritisation of risks*: Risk severity is represented by the aggregated risk score and their higher value indicates a greater severity of the associated risk. Based on aggregated risk score, the identified risks are ranked. The higher risk signifies the high priority of the risk.

4. Evaluation of the halal-related risks: a case study

A risk assessment problem of the HSC is taken as a case to explain the proposed method. The ranking of the risk element of halal integrity is determined using the proposed method. We determine the weight as well as the rank of the identified risk elements using the proposed framework.

4.1 Case description

Nowadays, the HSC become global resulting in increased complexities (Ali *et al.*, 2017). There has been a great deal of outsourcing of raw materials and ingredients to offshore companies. With such a complex and elongated supply chain, ensuring halal integrity and quality becomes much more challenging (Ngah *et al.*, 2022). The increased complexity creates a greater level of uncertainty and risk for halal businesses.

In the global halal business, halal integrity is of strategic importance as it relates to health, consumer trust and the performance of the company (Khan, Haleem, & Khan, 2020a, b). Although HSC partners strive to maintain halal integrity, it is vulnerable in many aspects, including raw materials and ingredients, processing, transportation and distribution. In order to assure the integrity of the halal product, it is necessary to identify these types of risks to enhance the consumer satisfaction (Khan *et al.*, 2022).

Halal production and the HSC are associated with various types of risks (Hamid and Rahman, 2022). Some additional risks such as halal integrity-related risks are associated with HSC in addition to standard supply chain risks (Khan *et al.*, 2020a, b; Handayani, Masudin, Haris, & Restuputri, 2021). It is important to understand that the risks associated with the HSC can be categorized as unexpected events that may disrupt the halalness of the product (Khan *et al.*, 2022). It has been observed that halal risks have occurred throughout the supply chain, including sourcing, warehousing, production and distribution. This results in the production of non-halal, low-quality, unhygienic consumables that negatively impact the brand image and its performance (Tseng *et al.*, 2022). Hence, understanding and managing the HSC-related risks are of utmost importance in achieving high performance and resilience. In order to assess the risks, associated with the HSC, the proposed methodology is applied as follows:

Step 1: Risks identification

A systematic literature review is conducted to identify halal-related risks. Further validation of these risks is provided by the expert's opinion. The finalised halal-related risks are presented in Table 2.

Step 2: Risk assessment through the expert's input using the neutrosophic number

In this step, experts evaluate each risk element based on the probability of occurrence and their impact. Two expert panels of five members have been formed to evaluate the risk element. The first panel consists of three industry professionals who are working in the halal industry at the management level and two persons working in the halal certification bodies. The second panel consists of five academic experts, which are working in the area of halal management. The evaluation of the expert's panel is obtained through the five-point linguistic scale and shown in Table 3.

Linguistic term	Equivalent SVTNNs
Very low	⟨(0.1, 0.1, 0.1, 0.1); 0.5, 0.3, 0.3⟩
Low	⟨(0.2, 0.3, 0.4, 0.5); 0.6, 0.2, 0.2⟩
Fairly low	⟨(0.3, 0.4, 0.5, 0.6); 0.7, 0.1, 0.1⟩
Medium	⟨(0.4, 0.5, 0.6, 0.7); 0.8, 0.0, 0.1⟩
Fairly high	⟨(0.5, 0.6, 0.7, 0.8); 0.8, 0.1, 0.1⟩
High	⟨(0.7, 0.8, 0.9, 1.0); 0.8, 0.2, 0.2⟩
Very high	⟨(1.0, 1.0, 1.0, 1.0); 0.9, 0.1, 0.1⟩

Source(s): Authors' own work

Table 1. Linguistic values of SVTNNs for the linguistic term

Risk	Brief description	References
Raw material status	The status of primary raw material in terms of the Halal (i.e. whether the raw is halal or not)	Khan *et al.* (2022), Ermis (2017), Ali and Suleiman (2018)
Raw material wholesomeness	The uncertainty of raw materials/ ingredients related to purity, hygiene and quality	Tieman (2017), Ali and Suleiman (2018)
Origins of raw materials	Insufficient or unreliable information is provided about the origin of the raw material	Khan *et al.* (2022), Soon, Chandia, and Regenstein (2017), Ali *et al.* (2017)
Unlawful ingredients/ emulsifiers for food preservation	In the case of halal products, the risk of using unlawful ingredients or emulsifiers is high	Zailani, Arrifin, Wahid, Othman, and Fernando (2010), Tan, Ali, Makhbul, and Ismail (2017)
Processing method risk	There is a chance of flaws or imprecisions in the design of Halal process methodologies, including slaughtering and cooking	Tang and Nurmaya Musa (2011), Giannakis and Papadopoulos (2016), Fuseini, Knowles, Hadley, and Wotton (2016)
Packaging process and materials	Halal products are at risk from packaging risks, such as the use of non-halal packaging materials	Tieman (2011), Giannakis and Papadopoulos (2016)
Centralised storage of products	Common storage facilities for halal and non-halal products, such as freezers, tracks, trolleys and racks	Tieman, van der Vorst, and CheGhazali (2012), Khan *et al.* (2018)
Animal welfare risk	Cruel treatment of animals for profit and causing them unnecessary suffering and pain	Giannakis and Papadopoulos (2016), Khan *et al.* (2018)
Common facility for the non-Halal product	Availability of common facilities for halal and non-halal products, such as trolleys, knives, and utensils, are subject to risks of halal integrity	Tieman (2011), Khan *et al.* (2022), Haleem and Khan (2017)
Halal certification	Certified from the non-creditable halal certification bodies/fake logo	Talib, Abu Bakar, and Chin (2016), Ali and Suleiman (2018)
Contamination within firm	Halal products and raw materials may be contaminated with non-Halal materials, waste, or intoxicants during their production, internal transportation, and storage	Khan *et al.* (2018), Haleem, Imran Khan, Khan, and Hafaz Ngah (2018)
Contamination in outsourcing activities	Contamination risk during outsourced activities such as transportation of Halal products with non-Halal materials, wastes, and intoxicants	Ngah, Zainuddin, & Thurasamy (2014), Haleem and Khan (2017)
Raw materials integrity	The raw material integrity is to prevent the raw material from addition/ substitution/mixing of any substance that diminishes the Halalness of the product	Manning and Soon (2014), Khan *et al.* (2018)
Process integrity	All processes, management systems, and facilities must be maintained in a manner that ensures halal compliance	Tan *et al.* (2017), Haleem *et al.* (2018)
Information/data integrity	Integrity in information refers to providing truthful and honest information to consumers	Demirci, Soon, and Wallace (2016), Ali *et al.* (2017), Fan, Li, Sun, and Cheng (2017)
People integrity	People integrity refers to the honesty and moral standards that an individual demonstrates	Christopher and Lee (2004), Ali *et al.* (2017)

Source(s): Authors' own work

Table 2.
Identified risks related to the halal integrity

Table 3. Halal supply chain risk assessment using linguistics scale by the expert panel

Risk	Industry Expert panel Probability	Impact	Academic Expert panel Probability	Impact
Raw material status	M	H	M	VH
Raw material wholesomeness	FL	VH	M	H
Origins of raw materials	M	FH	FL	H
Unlawful ingredients/emulsifiers for food preservation	M	FH	FL	H
Processing method risk	FL	H	FL	VH
Packaging process and materials	M	M	FL	FH
Centralised storage of products	L	VH	L	VH
Animal welfare risk	M	FL	FL	M
Common facility for the non-halal product	FL	M	L	H
Halal certification	FL	FL	FL	FL
Contamination within firm	L	FH	L	H
Contamination in outsourcing activities	FH	L	FH	L
Raw materials integrity	L	FH	L	M
Process integrity	FL	FL	L	FH
Information/data integrity	L	M	L	M
People integrity	FL	L	FL	L

Source(s): Authors' own work

Step 3: Calculate the severity of the risk

The expert's evaluation in terms of probability and impact of the risk is transformed into a neutrosophic number using Table 1. Based on the probability and impact, the severity of the risk element is calculated using Equation 1. For better understanding, the severity (provided by expert panel 1) of the "raw material status" is calculated as follows:

$$\text{Probability of risk occurrence (P)} = \text{M (assigned by expert panel 1)}$$

Convert linguistic value (in this case "medium: M") into SVTNN.

$P = \langle(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)\rangle$

$$\text{Impact of the risk (I)} = \text{H ((assigned by expert panel 1)}$$

Convert linguistic value (in this case "High: H") into SVTNN.

$I = \langle(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)\rangle$

Using equation (1),

$$\text{Severity} : S = P \otimes I$$

$$S = \langle(0.4, 0.5, 0.6, 0.7);\ (0.8, 0, 0.1)\rangle \otimes \langle(0.7, 0.8, 0.9, 1);\ (0.8, 0.2, 0.2)\rangle$$

These two SVTNNs are multiplied using neutrosophic operations:

$$S = \langle(0.4 \times 0.7, 0.5 \times 0.8, 0.6 \times 0.9, 0.7 \times 1;\ 0.8{\wedge}0.8, 0^{\vee}0.2, 0.1^{\vee}0.2\rangle$$

$$= \langle(0.28, 0.4, 0.54, 0.7)\ (0.8, 0.2, 0.2)\rangle$$

Similarly, for other risks (the remaining fifteen risks), severity is calculated and shown in Table 4.

Step 4: Aggregation of the experts' risk assessments

Risk	Probability	Impact	Severity
Risk assessment by industry expert panel			
Raw material status	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)⟩	⟨(0.28,0.4,0.54,0.7) (0.8,0.2,0.2)⟩
Raw material wholesomeness	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(1, 1, 1, 1); (0.9, 0.1, 0.1)⟩	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩
Origins of raw materials	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.42, 0.56); (0.8, 0.1, 0.1)⟩
Unlawful ingredients/emulsifiers for food preservation	⟨(0.4, 0.5, 0.6, 0.7; (0.8, 0, 0.1)⟩	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.42, 0.56); (0.8, 0.1, 0.1)⟩
Processing method risk	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)⟩	⟨(0.21, 0.32, 0.45, 0.6); (0.7, 0.2, 0.2)⟩
Packaging process and materials	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.16, 0.25, 0.36, 0.49); (0.8, 0, 0.1)⟩
Centralised storage of products	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(1, 1, 1, 1); (0.9, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩
Animal welfare risk	⟨(0.4, 0.5, 0.6, 0.7; (0.8, 0, 0.1)⟩	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.12, 0.2, 0.3, 0.42); (0.7, 0.1, 0.1)⟩
Common facility for the non-halal product	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.12, 0.2, 0.3, 0.42); (0.7, 0.1, 0.1)⟩
Halal certification	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.09, 0.16, 0.25, 0.36); (0.7, 0.1, 0.1)⟩
Contamination within firm	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩
Contamination in outsourcing activities	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩
Raw materials integrity	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩
Process integrity	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.09, 0.16, 0.25, 0.36); (0.7, 0.1, 0.1)⟩
Information/data integrity	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.08, 0.15, 0.24, 0.35); (0.6, 0.2, 0.2)⟩
People integrity	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.06, 0.12, 0.2, 0.3); (0.6, 0.2, 0.2)⟩
Risk assessment by academic expert panel			
Raw material status	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(1, 1, 1, 1); (0.9, 0.1, 0.1)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0.1, 0.1)⟩
Raw material wholesomeness	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)⟩	⟨(0.28, 0.4, 0.54, 0.7); (0.8, 0.2, 0.2)⟩
Origins of raw materials	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)⟩	⟨(0.21, 0.32, 0.45, 0.6); (0.7, 0.2, 0.2)⟩
Unlawful ingredients/emulsifiers for food preservation	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)⟩	⟨(0.21, 0.32, 0.45, 0.6); (0.7, 0.2, 0.2)⟩
Processing method risk	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(1, 1, 1, 1); (0.9, 0.1, 0.1)⟩	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩
Packaging process and materials	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.15, 0.24, 0.35, 0.48); (0.7, 0.1, 0.1)⟩
Centralised storage of products	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(1, 1, 1, 1); (0.9, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩
Animal welfare risk	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.12, 0.2, 0.3, 0.42); (0.7, 0.1, 0.1)⟩

(*continued*)

Table 4. Neutrosophic assessment of halal-related risks and their severity (by Industry expert panel)

Risk	Probability	Impact	Severity
Common facility for the non-Halal product	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)⟩	⟨(0.14, 0.24, 0.36, 0.5); (0.6, 0.2, 0.2)⟩
Halal certification	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.09, 0.16, 0.25, 0.36); (0.7, 0.1, 0.1)⟩
Contamination within firm	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.7, 0.8, 0.9, 1); (0.8, 0.2, 0.2)⟩	⟨(0.14, 0.24, 0.36, 0.5); (0.6, 0.2, 0.2)⟩
Contamination in outsourcing activities	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩
Raw materials integrity	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.08, 0.15, 0.24, 0.35); (0.6, 0.2, 0.2)⟩
Process integrity	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.5, 0.6, 0.7, 0.8); (0.8, 0.1, 0.1)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩
Information/data integrity	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0, 0.1)⟩	⟨(0.08, 0.15, 0.24, 0.35); (0.6, 0.2, 0.2)⟩
People integrity	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.06, 0.12, 0.2, 0.3); (0.6, 0.2, 0.2)⟩

Source(s): Authors' own work

Table 4.

Two individual expert panel evaluations are aggregated based on the neutrosophic operation using equation (2) and computational procedure to the aggregate severity (for the "raw material status" risk) as follows:

$$\text{Aggregated Severity} = \frac{1}{n}\sum_{i}^{n}\widetilde{p}^{i}$$

In our case, we have two experts panel, so, $n = 2$

$$\widetilde{S} = \frac{1}{2}\left(\widetilde{S}^{1} + \widetilde{S}^{2}\right)$$

$$= \frac{1}{2}\left(\widetilde{s}_1^1 + \widetilde{s}_1^2\right), \frac{1}{2}\left(\widetilde{s}_2^1 + \widetilde{s}_2^2\right), \frac{1}{2}\left(\widetilde{s}_3^1 + \widetilde{s}_3^2\right), \frac{1}{2}\left(\widetilde{s}_4^1 + \widetilde{s}_4^2\right);\ \alpha_{\widetilde{s^1}}{}^{\wedge}\alpha_{\widetilde{s^2}}, \theta_{\widetilde{s^1}}{}^{\vee}\theta_{\widetilde{s^2}}, \beta_{\widetilde{s^1}}{}^{\vee}\beta_{\widetilde{s^2}}\Big\rangle$$

$$= \frac{1}{2}\Big\langle(0.28, 0.4, 0.54, 0.7)\ (0.8, 0.2, 0.2)\Big\rangle + \Big\langle(0.4, 0.5, 0.6, 0.7);\ (0.8, 0.1, 0.1)\Big\rangle$$

$$= \Big\langle\ \frac{1}{2}\Big(0.28 + 0.4), \frac{1}{2}(0.4 + 0.5), \frac{1}{2}(0.54 + 0.6), \frac{1}{2}(0.7 + 0.7);\ 0.8^{\wedge}0.8, 0.2^{\vee}0.1, 0.2^{\vee}0.1\Big\rangle$$

$$= \langle(0.34, 0.45, 0.57, 0.7);\ (0.8, 0.2, 0.2)\rangle$$

The aggregated severity which is in the SVTNN is converted into a crisp number using equation 11 and shown for the "raw material status" risk score as follows:

$$\textit{risk score}\ (\widetilde{\text{S}}) = \frac{1}{12}(0.34 + 0.45 + 0.57 + 0.7)(2 + 0.8 - 0.2 - 0.2) = 0.412$$

$$= 0.412$$

The risk score for the other identified risk is calculated and provided in Table 5.

Risk	Severity (industry Expert panel)	Severity (academic Expert panel)	Aggregated severity	Aggregated risk score	Rank
Raw material Status	⟨(0.28,0.4,0.54,0.7) (0.8,0.2,0.2)⟩	⟨(0.4, 0.5, 0.6, 0.7); (0.8, 0.1, 0.1)⟩	⟨(0.34, 0.45, 0.57, 0.7); (0.8, 0.2, 0.2)⟩	0.412	1
Raw material wholesomeness	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.28, 0.4, 0.54, 0.7); (0.8, 0.2, 0.2)⟩	⟨(0.29, 0.4, 0.52, 0.65); (0.7, 0.2, 0.2)⟩	0.357	2
Origins of raw materials	⟨(0.2, 0.3, 0.42, 0.56); (0.8, 0.1, 0.1)⟩	⟨(0.21, 0.32, 0.45, 0.6); (0.7, 0.2, 0.2)⟩	⟨(0.21, 0.31, 0.44, 0.58); (0.7, 0.2, 0.2)⟩	0.293	4
Unlawful ingredients/ emulsifiers for food preservation	⟨(0.2, 0.3, 0.42, 0.56); (0.8, 0.1, 0.1)⟩	⟨(0.21, 0.32, 0.45, 0.6); (0.7, 0.2, 0.2)⟩	⟨(0.21, 0.31, 0.44, 0.58); (0.7, 0.2, 0.2)⟩	0.293	5
Processing method risk	⟨(0.21, 0.32, 0.45, 0.6); (0.7, 0.2, 0.2)⟩	⟨(0.3, 0.4, 0.5, 0.6); (0.7, 0.1, 0.1)⟩	⟨(0.255, 0.36, 0.475, 0.6); (0.7, 0.2, 0.2)⟩	0.324	3
Packaging process and materials	⟨(0.16, 0.25, 0.36, 0.49); (0.8, 0, 0.1)⟩	⟨(0.15, 0.24, 0.35, 0.48); (0.7, 0.1, 0.1)⟩	⟨(0.155, 0.245, 0.355, 0.485); (0.7, 0.1, 0.1)⟩	0.258	6
Centralised storage of products	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.2, 0.3, 0.4, 0.5); (0.6, 0.2, 0.2)⟩	0.257	7
Animal welfare risk	⟨(0.12, 0.2, 0.3, 0.42); (0.7, 0.1, 0.1)⟩	⟨(0.12, 0.2, 0.3, 0.42); (0.7, 0.1, 0.1)⟩	⟨(0.12, 0.2, 0.3, 0.42); (0.7, 0.1, 0.1)⟩	0.217	8
Common facility for the non-halal product	⟨(0.12, 0.2, 0.3, 0.42); (0.7, 0.1, 0.1)⟩	⟨(0.14, 0.24, 0.36, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.13, 0.22, 0.33, 0.46); (0.6, 0.2, 0.2)⟩	0.209	9
Halal certification	⟨(0.09, 0.16, 0.25, 0.36); (0.7, 0.1, 0.1)⟩	⟨(0.09, 0.16, 0.25, 0.36); (0.7, 0.1, 0.1)⟩	⟨(0.09, 0.16, 0.25, 0.36); (0.7, 0.1, 0.1)⟩	0.179	11
Contamination within firm	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩	⟨(0.14, 0.24, 0.36, 0.5); (0.6, 0.2, 0.2)⟩	⟨(0.12, 0.21, 0.32, 0.45); (0.6, 0.2, 0.2)⟩	0.202	10
Contamination in outsourcing activities	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩	0.176	12
Raw materials integrity	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩	⟨(0.08, 0.15, 0.24, 0.35); (0.6, 0.2, 0.2)⟩	⟨(0.09, 0.165, 0.26, 0.375); (0.6, 0.2, 0.2)⟩	0.163	14
Process integrity	⟨(0.09, 0.16, 0.25, 0.36); (0.7, 0.1, 0.1)⟩	⟨(0.1, 0.18, 0.28, 0.4); (0.6, 0.2, 0.2)⟩	⟨(0.095, 0.17, 0.265, 0.38); (0.6, 0.2, 0.2)⟩	0.167	13
Information/data integrity	⟨(0.08, 0.15, 0.24, 0.35); (0.6, 0.2, 0.2)⟩	⟨(0.08, 0.15, 0.24, 0.35); (0.6, 0.2, 0.2)⟩	⟨(0.08, 0.15, 0.24, 0.35); (0.6, 0.2, 0.2)⟩	0.150	15
People integrity	⟨(0.06, 0.12, 0.2, 0.3); (0.6, 0.2, 0.2)⟩	⟨(0.06, 0.12, 0.2, 0.3); (0.6, 0.2, 0.2)⟩	⟨(0.06, 0.12, 0.2, 0.3); (0.6, 0.2, 0.2)⟩	0.125	16

Source(s): Authors' own work

Table 5.
Risk scores of halal-related risks

Step 5: Prioritisation of risks

In this step, the risk is prioritised on the basis of the risk score. The higher rank is provided to that risk which has the highest risk score. The ranking of the risk element is shown in Table 5.

5. Results and discussions

The proposed method is successfully applied to evaluate the risk of halal integrity. The ranking of identified risks corresponds to their risk score which denotes the degree of interruption towards maintaining the halal integrity. Based on the risk score, "raw material status" risk has the first rank with a risk score of 0.412. The halalness of the product very much depends on the status (i.e. halal or non-halal) of its raw material/ingredient, and the impact of the raw material status is very high in the context of halal integrity. As a result, it is imperative to ensure that all the ingredients in the product are in good condition and halal (Rishelin and Ardi, 2020). The second rank risk is "raw material wholesomeness", which is associated with the material used. The raw material should have wholesome along with the halal. Khan *et al.* (2022) also found that the wholesomeness of the raw material is one of the major risks of HSC. To mitigate this risk the halal industry should select credible suppliers which provide better-quality products. Apart from this, the companies should provide a supplier development program to maintain the wholesomeness of the product. The next risk in the "processing method" has a risk score of 0.324. Through the improvement of processes and processing methods, the firm can mitigate such risks. Khan *et al.* (2022) also found that the processing method is one of the significant risks in the HSC. Furthermore, the next risk "origin of the raw material" needs to be addressed. This risk can be mitigated through the implementation of the traceability system in the HSC. The traceability system provides all the information regarding the raw material origin and its processing method. In order to provide a robust traceability system, blockchain technologies can be used (Tan, Gligor, & Ngah, 2020).

The use of "unlawful ingredients/emulsifiers for food preservation" is also a threat to halal integrity. This risk can be handled using the halal ingredient/emulsifier which is assessed and certified by a credible certification body. The "packaging process and materials" is the next priority risk. There is a high chance to use non-halal material for packaging purposes. This risk can be mitigated through the process design for packaging and the use of halal packaged material instead of non-halal packaging materials. In addition to this, there is proper segregation between halal and non-halal products. The next risk in this row is the risk of animal welfare risk. The animal treatment is humanised during husbandry, transportation and processing.

Previous literature also reveals that some firms use the common facility for halal and non-halal products. To mitigate this risk, proper ritual cleaning should be done before production. Further, the "contamination within the firm" has the next rank with a risk score of 0.202. To mitigate this risk, proper segregation in the production, transportation and storage of halal and non-halal products. This can be accomplished by segregating the production equipment (such as knives and utensils), internal transportation infrastructure (trollies) and storage infrastructure (rakes, containers) for the halal and non-halal products. In addition, proper cleaning is also recommended before the use of the production equipment and supporting mechanism. The next risk is the halal certification-related risk such as acceptance of the non-creditable halal certification bodies/fake logo. This risk can be minimised by taking the initiative to develop a globally accepted halal certification/harmonised halal certification system. Halal producers need to use a halal-certified transportation system that is dedicated only to transporting halal products. In case of unavailability of the halal-certified transportation system, the product should be packed in such a way contamination is not permissible.

Additionally, "process integrity" is with a risk score of 0.167. To maintain process integrity, the process needs to be designed and operated according to the standards of credible certification systems. Next in this row is "raw materials integrity" risk with a risk score is 0.165. The selection of a credible supplier and supply chain partner maintains the integrity of raw materials (Handayani *et al.*, 2021). The raw material integrity can be the "information/data integrity" is another risk with a risk score of 0.150. An effective traceability system maintains information integrity throughout the HSC by providing credible information to the stakeholders (Alamsyah, Hakim, & Hendayani, 2022). Finally, the lowest priority risk among the identified risks is "people integrity" which can be addressed by developing honest and responsible people.

6. Implications of the research

This study presents a novel risk assessment method using the neutrosophic theory to overcome the limitations of the conventional method by introducing the concept of neutrosophic numbers. The neutrosophic number effectively addresses the issue of linguistic subjectivity, inconsistent information and uncertainty in the expert's opinion. As the risks are highly uncertain, the neutrosophic number is used for dealing with the present uncertainty in the expert's opinion. This method can be applied to individual as well as group decision-making for risk assessment for the supply chain. This method is utilised for other risk assessments such as supply chain risks, sustainability-related risks and green supply chain risks etc. In addition to this, this also helps the managers to assess the risk in the HSC and take the appropriate action. The proposed risk assessment framework is generic for different HSCs such as halal food supply chain, halal cosmetic supply chain and halal pharmaceutical supply chain.

This study has a certain implication for the HSC in addition to the methodological contribution. The risk regarding the "halal integrity" is identified which can be utilised for risk management in the HSC. Further, through the application of the proposed risk assessment method, risks are prioritised according to their risk score. High-priority risks are needed to be mitigated first with an effective mitigation strategy. In addition, the insight into the prioritisation of the risk provided by this study helps the managers/policy planner to develop the appropriate strategies/policies regarding minimising the risk across the supply chain and assure halal integrity.

7. Conclusion, limitation and future scope

In this study, a novel method for risk assessment is proposed using the neutrosophic theory. This study effectively uses the SVTNNs to convert the linguistic assessment of the expert under an uncertain environment. A case study of the HSC is undertaken to illustrate the adopted methodology. The literature review identified sixteen risk elements of halal integrity that were further validated by the expert panel. A linguistic value of risk is used by the two expert panels to evaluate the probability of occurrence of these risks and their impact. These linguistic values are converted into an SVTNN. Further, the severity of each risk is determined using neutrosophic operations. Finally, the risk score of the finalised risks elements is calculated and risk elements are prioritised as per their risk score. This study reveals that raw materials-related risks are high priority such as "raw material status", "raw material wholesomeness" and "origin of raw material" while the people "information integrity" and "people integrity" are low priority risks.

Risk assessment in HSCs can be effectively achieved using the proposed method. The advantage of this method is to capture real-life situations by introducing neutrosophic numbers. This method can be used to assess the risk in sustainability, green practices and

HSC. This study used the trapezoidal neutrosophic number to convert the linguistic scale, while the triangular neutrosophic number can be used in future studies. The interval type neutrosophic number can also be utilised to assess the risk in various domains. Additionally, this method can be extended to other risk measurement domains such as risk priority umbers (RPN) and knowledge-based risk models.

References

Ab Talib, M. S., & Zulfakar, M. H. (2023). Sustainable halal food supply chain management in a small rentier halal market. *Arab Gulf Journal of Scientific Research*, ahead-of-print(ahead-of-print). doi: 10.1108/agjsr-11-2022-0251.

Abdalkrim, G., & Guizani, M. (2022). Analyzing external environmental, strategic alliance, and strategic alliance of Kingdom of Saudi Arabia firms – an empirical research. *Arab Gulf Journal of Scientific Research*, *40*(4), 347–363. doi: 10.1108/AGJSR-07-2022-0115.

Abdel-Basset, M., Mohamed, M., Hussien, A., & Sangaiah, A. (2017). A novel group decision-making model based on triangular neutrosophic numbers. *Soft Computing*, *22*(20), 6629–6643. doi: 10.1007/s00500-017-2758-5.

Abdel-Basset, M., Gunasekaran, M., Mohamed, M., & Smarandache, F. (2018). A novel method for solving the fully neutrosophic linear programming problems. *Neural Computing and Applications*, *31*. doi: 10.1007/s00521-018-3404-6.

Alamsyah, A., Hakim, N., & Hendayani, R. (2022). Blockchain-based traceability system to support the Indonesian halal supply chain ecosystem. *Economies*, *10*(6), 134. doi: 10.3390/economies10060134.

Ali, M., & Suleiman, N. (2018). Eleven shades of food integrity: A halal supply chain perspective. *Trends In Food Science and Technology*, *71*, 216–224. doi: 10.1016/j.tifs.2017.11.016.

Ali, M., Tan, K., & Ismail, M. (2017). A supply chain integrity framework for halal food. *British Food Journal*, *119*(1), 20–38. doi: 10.1108/bfj-07-2016-0345.

Amer, M. (2023). Halal standards' implementation in Palestinian food sector: Its drivers and impact on performance. *Arab Gulf Journal of Scientific Research*, ahead-of-print(ahead-of-print). doi: 10.1108/agjsr-09-2022-0168.

Anis, Z. B., Iqbal, R., Nazir, W., & Khalid, N. (2022). Technological advances in supply chain of processed foods during COVID-19: A review. *Arab Gulf Journal of Scientific Research*, Vol. ahead-of-print No. ahead-of-print.

Awang, A., Ghani, A. T., Abdullah, L., & Ahmad, M. F. (2018). A DEMATEL method with single valued neutrosophic set (SVNS) in identifying the key contribution factors of Setiu Wetland's coastal erosion. In *AIP Conference Proceedings*, (Vol. 1974, 020011), AIP Publishing. doi: 10.1063/1.5041542.

Balfaqih, H., Nopiah, Z., Saibani, N., & Al-Nory, M. (2016). Review of supply chain performance measurement systems: 1998–2015. *Computers In Industry*, *82*, 135–150. doi: 10.1016/j.compind.2016.07.002.

Behzadi, G., O'Sullivan, M., Olsen, T., & Zhang, A. (2018). Agribusiness supply chain risk management: A review of quantitative decision models. *Omega*, *79*, 21–42. doi: 10.1016/j.omega.2017.07.005.

Biswas, P., Pramanik, S., & Giri, B. (2015). TOPSIS method for multi-attribute group decision-making under single-valued neutrosophic environment. *Neural Computing and Applications*, *27*(3), 727–737. doi: 10.1007/s00521-015-1891-2.

Chand, M., Raj, T., & Shankar, R. (2015). Weighted-ISM technique for analysing the competitiveness of uncertainty and risk measures in supply chain. *International Journal of Logistics Systems and Management*, *21*(2), 181. doi: 10.1504/ijlsm.2015.069374.

Cheng, L., Guo, X., Li, X., & Yu, Y. (2022). Data-driven ordering and transshipment decisions for online retailers and logistics service providers. *Transportation Research Part E: Logistics and Transportation Review*, *161*, 102684. doi: 10.1016/j.tre.2022.102684.

Christopher, M., & Lee, H. (2004). Mitigating supply chain risk through improved confidence. *International Journal of Physical Distribution and Logistics Management*, *34*(5), 388–396. doi: 10.1108/09600030410545436.

Demirci, M. N., Soon, J. M., & Wallace, C.A. (2016). Positioning food safety in halal assurance. *Food Control*, *70*, 257–270.

Dong, Q., & Cooper, O. (2016). An orders-of-magnitude AHP supply chain risk assessment framework. *International Journal of Production Economics*, *182*, 144–156. doi: 10.1016/j.ijpe.2016.08.021.

Ermis, E. (2017). Halal status of enzymes used in food industry. *Trends in Food Science and Technology*, *64*, 69–73.

Fan, H., Li, G., Sun, H., & Cheng, T. (2017). An information processing perspective on supply chain risk management: Antecedents, mechanism, and consequences. *International Journal of Production Economics*, *185*, 63–75. doi: 10.1016/j.ijpe.2016.11.015.

Fuseini, A., Knowles, T., Hadley, P., & Wotton, S. (2016). Halal stunning and slaughter: Criteria for the assessment of dead animals. *Meat Science*, *119*, 132–137. doi: 10.1016/j.meatsci.2016.04.033.

Gebhardt, M., Spieske, A., Kopyto, M., & Birkel, H. (2022). Increasing global supply chains' resilience after the COVID-19 pandemic: Empirical results from a Delphi Study. *Journal of Business Research*, *150*, 59–72. doi: 10.1016/j.jbusres.2022.06.008.

Giannakis, M., & Papadopoulos, T. (2016). Supply chain sustainability: A risk management approach. *International Journal of Production Economics*, *171*, 455–470. doi: 10.1016/j.ijpe.2015.06.032.

Haleem, A., Imran Khan, M., Khan, S., & Hafaz Ngah, A. (2018). Assessing barriers to adopting and implementing halal practices in logistics operations. *IOP Conference Series: Materials Science and Engineering*, *404*, 012012. doi: 10.1088/1757-899x/404/1/012012.

Haleem, A., & Khan, M. (2017). Towards successful adoption of Halal logistics and its implications for the stakeholders. *British Food Journal*, *119*(7), 1592–1605.

Hamid, A. A., & Rahman, N. S. (2022). Halal logistics and supply chain management in Asia, the West and the Middle East. *Halal Logistics and Supply Chain Management*, 7–16. doi: 10.4324/9781003223719-3.

Handayani, D. I., Masudin, I., Haris, A., & Restuputri, D. P. (2021). Ensuring the halal integrity of the food supply chain through halal suppliers: A bibliometric review. *Journal of Islamic Marketing*, *13*(7), 1457–1478. doi: 10.1108/jima-10-2020-0329.

Hashmi, N., Aqib Jalil, S., & Javaid, S. (2022). A multi-objective model for closed-loop supply chain network based on carbon tax with two fold uncertainty: An application to leather industry. *Computers and Industrial Engineering*, *173*, 108724. doi: 10.1016/j.cie.2022.108724.

Hashmi, N., Jalil, S. A., & Javaid, S. (2021). Carbon footprint based multi-objective supplier selection problem with uncertain parameters and fuzzy linguistic preferences. *Sustainable Operations and Computers*, *2*, 20–29. doi: 10.1016/j.susoc.2021.03.001.

Heckmann, I., Comes, T., & Nickel, S. (2015). A critical review on supply chain risk-definition, measure and modeling. *Omega*, *52*, 119–132.

Javaid, M., Khan, S., Haleem, A., & Rab, S. (2022). Adoption of modern technologies for Implementing Industry 4.0: An integrated MCDM approach. *Benchmarking: An International Journal*. doi: 10.1108/bij-01-2021-0017.

Javaid, T., & Siddiqui, D. (2018). Supply chain responsiveness and supply chain performance: The role of supply chain risk management. *SSRN Electronic Journal*. doi: 10.2139/ssrn.3285077.

Khan, M. I., Haleem, A., & Khan, S. (2018). Defining halal supply chain management. *Supply Chain Forum: An International Journal*, *19*(2), 122–131.

Khan, S., Haleem, A., & Khan, M. I. (2020a). Assessment of risk in the management of halal supply chain using fuzzy BWM method. *Supply Chain Forum: An International Journal*, *22*(1), 57–73. doi: 10.1080/16258312.2020.1788905.

Khan, S., Haleem, A., & Khan, M. I. (2020b). Risk management in halal supply chain: An integrated fuzzy delphi and DEMATEL approach. *Journal of Modelling in Management*, *16*(1), 172–214. doi: 10.1108/jm2-09-2019-0228.

Khan, S., Haleem, A., & Khan, M. I. (2022). Risk assessment model for halal supply chain using an integrated approach of IFN and D number. *Arab Gulf Journal of Scientific Research*, ahead-of-print(ahead-of-print). doi: 10.1108/agjsr-09-2022-0160.

Khan, S., Khan, M. I., Haleem, A., & Jami, A. R. (2019). Prioritising the risks in halal food supply chain: An MCDM approach. *Journal of Islamic Marketing*, *13*(1), 45–65. doi: 10.1108/jima-10-2018-0206.

Khan, S. Haleem, A., Ngah, A. H. and Khan, M. I. (2023). Exploration of risks with halal logistics: A case of emerging economy. *Journal of Global Operations and Strategic Sourcing [Preprint]*. doi: 10.1108/jgoss-01-2022-0001.

Lin, S., Li, C., Xu, F., Liu, D., & Liu, J. (2018). Risk identification and analysis for new energy power system in China based on D numbers and decision-making trial and evaluation laboratory (DEMATEL). *Journal of Cleaner Production*, *180*, 81–96. doi: 10.1016/j.jclepro.2018.01.153.

Liu, X., Zhou, Y., & Gao, S. (2022). Intellectual structure in supply chain risk management from 2000 to 2022: A review based on text mining approach. *Sustainability*, *14*(23), 16245. doi: 10.3390/su142316245.

Mangla, S. K., Kumar, P., & Barua, M. K. (2015). Risk analysis in green supply chain using fuzzy AHP approach: A case study. *Resources, Conservation and Recycling*, *104*, 375–390. doi: 10.1016/j.resconrec.2015.01.001.

Manning, L., & Soon, J. (2014). Developing systems to control food adulteration. *Food Policy*, *49*, 23–32. doi: 10.1016/j.foodpol.2014.06.005.

Muneeb, S. M., Asim, Z., & Adhami, A. Y. (2019). A multi-criteria decision making model for the optimal planning of municipal solid waste under uncertainty. *International Journal of Multicriteria Decision Making*, *8*(2), 105. doi: 10.1504/ijmcdm.2019.106903.

Ngah, A. H., Tuan Mansor, T. M., Gabarre, C., Rahi, S., Khan, S., & Ahmad, R. (2022). I love my cosmetics: Educated young Muslim's behaviour of non-halal Certified Cosmetics. *Journal of Islamic Marketing*, ahead-of-print(ahead-of-print). doi: 10.1108/jima-06-2021-0196.

Ngah, A. H., Zainuddin, Y., & Thurasamy, R. (2014). Barriers and enablers in adopting halal transportation services: A study of Malaysian halal manufacturers. *International Journal of Business and Management*, *2*(2), 49–70. doi: 10.1108/JIMA-03-2014-0027.

Omar, E. N., & Jaafar, H. S. (2011). Halal supply chain in the food industry - a conceptual model. 2011. *IEEE Symposium on Business, Engineering and Industrial Applications (ISBEIA)*. doi: 10.1109/isbeia.2011.6088842.

Qazi, A., Quigley, J., Dickson, A., & Ekici, Ş. Ö. (2017). Exploring dependency based probabilistic supply chain risk measures for prioritising interdependent risks and strategies. *European Journal of Operational Research*, *259*(1), 189–204. doi: 10.1016/j.ejor.2016.10.023.

Rishelin, N., & Ardi, R. (2020). Prioritizing risks of halal meat supply chain in Indonesian downstream sector using DEMATEL-based ANP. 2020. *IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*. doi: 10.1109/ieem45057.2020.9309875.

Salama, A., Broumi, S., & Smarandache, F. (2014). Neutrosophic crisp open set and neutrosophic crisp continuity via neutrosophic crisp ideals. *International Journal Of Information Engineering and Electronic Business*, *6*(3), 1–8. doi: 10.5815/ijieeb.2014.03.01.

Shan, X., Xiong, S., & Zhang, C. (2023). Mitigating supply disruption risks by diversifying competing suppliers and using sales effort. *International Journal of Production Economics*, *255*, 108637. doi: 10.1016/j.ijpe.2022.108637.

Shankar, R., Choudhary, D., & Jharkharia, S. (2018). An integrated risk assessment model: A case of sustainable freight transportation systems. *Transportation Research Part D: Transport and Environment*, *63*, 662–676. doi: 10.1016/j.trd.2018.07.003.

Simić, V., Milovanović, B., Pantelić, S., Pamučar, D., & Tirkolaee, E. B. (2023). Sustainable route selection of petroleum transportation using a type-2 neutrosophic number based Itara-EDAS model. *Information Sciences*, *622*, 732–754. doi: 10.1016/j.ins.2022.11.105.

Singh, R., Khan, S., & Dsilva, J. (2022). A framework for assessment of critical factor for Circular Economy Practice Implementation. *Journal of Modelling in Management*. doi: 10.1108/jm2-06-2021-0145.

Singh, R., Khan, S., Dsilva, J., & Centobelli, P. (2023). Blockchain integrated IOT for Food Supply Chain: A grey based Delphi-DEMATEL approach. *Applied Sciences*, *13*(2), 1079. doi: 10.3390/app13021079.

Smarandache, F. (1998). *Neutrosophy: Neutrosophic probability, set, and logic*. Rehoboth: American Research Press.

Song, M., Ma, X., Zhao, X., & Zhang, L. (2022). How to enhance supply chain resilience: A logistics approach. *The International Journal of Logistics Management*, *33*(4), 1408–1436. doi: 10.1108/ijlm-04-2021-0211.

Soon, J., Chandia, M., & Regenstein, J. (2017). Halal integrity in the food supply chain. *British Food Journal*, *119*(1), 39–51. doi: 10.1108/bfj-04-2016-0150.

Talib, M. S. A., Abu Bakar, A. H., & Chin, T. A. (2016). Can halal certification influence logistics performance?. *Journal of Islamic Marketing*, *7*(4), 461–475. doi: 10.1108/JIMA-02-2015-0015.

Tan, K., Ali, M., Makhbul, Z., & Ismail, A. (2017). The impact of external integration on halal food integrity. *Supply Chain Management: An International Journal*, *22*(2), 186–199. doi: 10.1108/scm-05-2016-0171.

Tan, A., Gligor, D., & Ngah, A. (2020). Applying blockchain for halal food traceability. *International Journal of Logistics Research and Applications*, *25*(6), 947–964. doi: 10.1080/13675567.2020.1825653.

Tang, O., & Nurmaya Musa, S. (2011). Identifying risk issues and research advancements in supply chain risk management. *International Journal of Production Economics*, *133*(1), 25–34. doi: 10.1016/j.ijpe.2010.06.013.

Tian, D., Chen, J., & Wu, X. (2022). A two stage risk assessment model based on interval-valued fuzzy numbers and risk attitudes. *Engineering Applications of Artificial Intelligence*, *114*, 105086. doi: 10.1016/j.engappai.2022.105086.

Tieman, M. (2011). The application of halal in supply chain management: In-depth interviews. *Journal of Islamic Marketing*, *2*(2), 186–195.

Tieman, M. (2017). Halal risk management: Combining robustness and resilience. *Journal of Islamic Marketing*, *8*(3), 461–475. doi: 10.1108/jima-06-2015-0041.

Tieman, M., van der Vorst, J., & Che Ghazali, M. (2012). Principles in halal supply chain management. *Journal of Islamic Marketing*, *3*(3), 217–243. doi: 10.1108/17590831211259727.

Tseng, M. -L., Ha, H. M., Tran, T. P., Bui, T. -D., Lim, M. K., Lin, C. -W., & Helmi Ali, M. (2022). Data-driven on sustainable food supply chain: A comparison on halal and non-halal food system. *Journal of Industrial and Production Engineering*, *39*(6), 430–457. doi: 10.1080/21681015.2022.2040622.

Vafadarnikjoo, A., Mishra, N., Govindan, K., & Chalvatzis, K. (2018). Assessment of consumers' motivations to purchase a remanufactured product by applying Fuzzy Delphi method and single valued neutrosophic sets. *Journal of Cleaner Production*, *196*, 230–244. doi: 10.1016/j.jclepro.2018.06.037.

Wang, H., Smarandache, F., Zhang, Y. -Q., & Sunderraman, R. (2010). Single valued neutrosophic sets. *Rev Air Force Acad*, *17*(1), 10–14.

Wiengarten, F., Humphreys, P., Gimenez, C., & McIvor, R. (2016). Risk, risk management practices, and the success of supply chain integration. *International Journal of Production Economics*, *171*, 361–370. doi: 10.1016/j.ijpe.2015.03.020.

Zailani, S., Arrifin, Z., Wahid, N. A., Othman, R., & Fernando, Y. (2010). Halal traceability and halal tracking systems in strengthening halal food supply chain for food industry in Malaysia (a review). *Journal of Food Technology*, *8*(3), 74–81.

Zulfakar, M. H., Anuar, M. M., & Talib, M. S. (2014). Conceptual framework on halal food supply chain integrity enhancement. *Procedia - Social and Behavioral Sciences*, *121*, 58–67. doi: 10.1016/j.sbspro.2014.01.1108.

Further reading

Ali, M., Tan, K., Pawar, K., & Makhbul, Z. (2014). Extenuating food integrity risk through supply chain integration: The case of halal food. *Industrial Engineering and Management Systems*, *13*(2), 154–162.

Haleem, A., Khan, M.I. and Khan, S. (2020) 'Conceptualising a framework linking Halal Supply Chain Management with sustainability: An India Centric Study', *Journal of Islamic Marketing*, *12*(8), pp. 1535–1552. doi: 10.1108/jima-07-2019-0149.

Corresponding author

Shahbaz Khan can be contacted at: shahbaz.me12@gmail.com