Journal of Cleaner Production 228 (2019) 786–800

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Framework for evaluating risks in food supply chain: Implications in food wastage reduction

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ARTICLE INFO

Article history:
Received 12 June 2018
Received in revised form
25 March 2019
Accepted 24 April 2019
Available online 25 April 2019

Keywords:
Supply chain risk
Grey theory
DEMATEL
Supply chain disruption
Food wastage
Sustainable food supply chain

ABSTRACT

Over the years, food supply chains (FSCs) have faced various challenges, including supply chain interruptions. Previous studies focused only on household food waste. In this study, the FSCs risks is connected with food wastage to develop sustainable framework to reduce food waste. A Pareto analysis is developed for risk identification based on feedback from 130 experts from food companies. Finally, a blended grey-based Decision-Making Trial and Evaluation Laboratory (DEMATEL) model has been proposed to assess the relationships among the identified major risks in FSCs. The five risks of greatest priority include: lack of skilled personnel, poor leadership, failure within the IT system, capacity, and poor customer relationship. The risk mitigation strategies for these risks are also presented. The proposed model is applied to food processing companies in Bangladesh to establish a sustainable business policy to minimize food wastage. These results can guide managers and practitioners to formulate resilient strategies to mitigate the identified risks, thereby minimizing food wastage and lead to food safety, security and sustainability across the food supply chain. The proposed model can be extended to address sustainability risk and be integrated to the internet of things for planning, monitoring, controlling, and optimizing supply chains in real time.

1. Introduction

Supply chains are becoming more vulnerable due to an increase in disruptive events from man-made and natural causes (Ali et al., 2018; Govindan, 2017). Food supply chains (FSCs) are more complicated than other manufacturing/service supply chains as food is a perishable commodity (Ali and Nakade, 2018; Singh et al., 2018). Food is an essential and basic human requirements for survival. Over the years, FSCs have faced continuous challenges from multiple factors which include food price volatility, climate controlled variability, food wastages, food and nutrition security, power and governance issues, and distribution of value within FSCs (Gokarn and Kuthambalayan, 2017; Fredriksson and Liljestrand, 2015).

FSC risk assessment is essential to avoid food and resource wastage and helps enterprises build resilient strategies for food security. Christopher and Peck (2004) presented that the current food business challenges are managing and mitigating risks through creating resilient supply chains. Examining risks in FSCs can enhance the sustainability, equitability, and performance of FSCs (Govindan, 2017).

To provide safe and reliable products, every supply chain member must recognize risks both within and outside of their networks. Multiple studies recommend organizations need to follow a formal structure to identify and evaluate supply chain risks and finally to implement a plan to mitigate risks for minimizing food wastage (de Oliveira et al., 2017; Khan and Burnes, 2007) The result will be to achieve high supply chain performance through reducing uncertainties and vulnerabilities in the supply chain (Mangla et al., 2015a; Mangla et al., 2016).

Recently, FSC risk assessment and risk management have received concern at national (Song and Zhuang, 2017) and

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https://doi.org/10.1016/j.jclepro.2019.04.322
0959-6526/

List of notations and abbreviations

FSCs	Food Supply Chains
DEMATEL	Decision-Making Trial and Evaluation Laboratory
AHP	Analytic Hierarchy Process
GST	Grey System Theory
R1-R10	Listed Food Risks
$\otimes$ P	Grey Number
P	Lower value of a grey number $\otimes$P
$\overline{P}$	Upper value of a grey number $\otimes P$
i,j,n	Criteria
k	Respondents
P_{ij}^{k}	Grey number for an expert k
$\underline{P}_{ij}^{k}$	Lower grey values of a grey number $\otimes P_{ij}^{k}$
$\overline{P}_{ij}^{k}$	Upper grey values of a grey number $\otimes P_{ij}^{k}$
$\tilde{\underline{P}}_{ij}^{k}$	Normalized lower grey values of a grey number $\otimes P_{ij}^{k}$
$\tilde{\overline{P}}_{ij}^{k}$	Normalized upper grey values of a grey number $\otimes P_{ij}^{k}$
Δ_{min}^{max} :	Difference between max normalized upper grey values and min normalized lower grey values
Q_{ij}^{k}	Normalized crisp value
$A_{n\times n}$	Pairwise comparison relation matrix for n criteria
$\overline{a}_{ij}$	Average relation matrix
M	Normalized direct-relation matrix
I	Identity matrix
T	Total relation matrix
D_i	Sum of row values of criteria in total relation matrix
R_j	Sum of column values of criteria in total relation matrix

international (de Oliveira et al., 2017) levels. Song and Zhuang (2017) developed a game-theoretic model to study optimal risk management policy for FSC. Nakandala et al. (2017) proposed a hybrid model consisting both hierarchical holographic modeling and fuzzy logic to assess the risk in FSCs. Xiaoping (2016) proposed a fuzzy analytic hierarchy process (AHP) model to examine safety risks in FSCs.

However, the majority of these studies did not consider the interactions among diversified risks that are present in today's complex supply chains. In addition, previous studies ignored how the FSCs' risk assessment framework can guide managers to optimize resource. Balaji and Arshinder (2016) demonstrated the causes of food wastage in Indian FSCs. Recently, Schanes et al. (2018) investigated household food waste practices and policy implications. Sun et al. (2018) showed the impact of food wastage on the environment and water resources. Efficient and effective FSCs are important concerns for both emerging and developed economy (Govindan, 2017).

The complexity of FSCs and corresponding food wastage has increased significantly; resulting in a huge loss of natural resources (Mangla et al., 2018). Exploring risks in the complex FSCs to understand the implications to enable reducing food wastage and optimizing resources in an FSC would be valuable. Limited academic and practical studies exist on how the risk assessment framework examines the cause-effect relationships among various factors in a supply chain. This research addresses the following research questions:

(a) What are the key FSC risks?
(b) What are the interactions/interrelationships among these key FSC risks?
(c) How will the key risks be classified into cause and effect groups to provide practical insights for industrial managers?
(d) How will these risks be useful to reduce food wastage?

This study integrates the grey system theory (GST) and the DEMATEL method to assess the risk in FSCs. As well, the implications of FSCs' risk assessment framework to minimize food wastage in supply chains is studied. The strengths of the GST and DEMATEL methods are combined to develop an effective and novel decision support tool for the risk assessment in FSCs. GST handles the uncertainty of human subjective judgment with discrete data (Xia et al., 2015; Bai and Sarkis, 2010). The advantage of GST is its ability to make logical results using a small set of information (Moktadir et al., 2018b; Memon et al., 2015). Whereas, DEMATEL method captures cause-effect relations among risk criteria through digraph, but is unable to overcome the uncertainty of the risk criteria (Bai and Sarkis, 2013; Tadić et al., 2014). The combination of GST and DEMATEL (grey-DEMANTEL) models the uncertain and ambiguous problems in human judgment and overcomes the drawback of the DEMATEL method providing more reliable results for FSC risk analysis.

The grey-DEMATEL method used in this study constructs the relations between FSC risk factors in a structural way. The risks are organized into cause-effect groups using a causal diagram. This diagram assists decision-makers to understand the complex relations among the risks for effective business management.

The proposed framework was applied to an emerging FSC from Bangladesh. Many Bangladeshi food processing companies have developed ways to be resilient and sustainable by identifying vulnerabilities and food wastage in the FSC. As a case study, a company in the FSC inspected the interactions among the supply chain risks for reducing food wastage caused by the risks in the FSC. The case company was also interested in building a structural framework to assess the supply chain risks. Section 4 provides details on applying the proposed framework to this company.

The paper is structured whereby Section 2 outlines the research background on risk assessment, and presents the risk in the FSC. Then, Section 3 presents a brief discussion on GST and the DEMATEL method. In Section 4, the proposed grey-DEMATEL method is applied to evaluate the FSC risk of a food processing company in Bangladesh. The results and the sensitivity analysis are discussed in Section 5. The final section prsents the conclusions with the limitations of the study along with the opportunities for further research.

2. Literature review

The highlights and research gaps in the literature relating to FSC, risk assessment modeling of FSC and food wastage and the grey system theory and DEMATEL models are presented sequentially.

2.1. Food supply chain risk

A supply chain is a network of organizations, people, activities, technology, and information to convert raw material into finished products that are shipped or supplied to the consumer (Miranbeigi et al., 2015). Risks are inherent and interconnected in supply chains. A wide variety of supply chain risk classifications exist (Heckmann et al., 2015; Ho et al., 2015). The most widely accepted supply chain risk classification is from Tang (2006), and is followed for assessing FSC in this study.

Tang (2006) categorized supply chain risk into disruption risks and operational risks. Disruption risks are caused by human-made and natural disasters; such as: terrorist attacks, floods, earthquakes, hurricanes, economic crises (Diabat et al., 2012; Nakandala et al., 2017). Operational risks result while executing the business process or supply chain activities (Xiaoping, 2016). According to Heckmann et al. (2015), operational risks occur due to the inherent uncertainties of supply, demand, market price, and cost; for example, machine, equipment or facility failure, supply failure and management failure. Such risk factors create a disturbance in the supply chain and require proper assessing to formulate risk mitigation strategies. Table 1 summarizes some common operational risks, both internal and external to the company, which have appeared in the literature. As seen in Table 1, some operational risks are internal to firms, whereas some are external in nature.

2.2. Risk assessment in the food supply chain and food wastage

To minimize food wastage, risk assessment for managing FSC involves identifying and assessing supply chain risks to develop appropriate risk mitigation strategies (ISO, 2009; Leitch, 2010; Wu et al., 2006), food waste management strategies (Stancu et al., 2016) and for business continuity management plans (Torabi et al., 2016). Literature that combines both FSCs risks and food waste is not current or well established. Several researchers focus only on the FSCs risks or the food wastage management. For example, Schanes et al. (2018) reviewed the literature of household food waste practices and related policy implications; Williams et al. (2012) discussed the reasons for household food waste.

Table 2 summarizes methods applied to assess FSC risk. Most of the authors applied AHP and fuzzy-based methods. One of the major limitations of these methods is they do not consider the relation among the risk factors. In real life, relations among supply chain risk factors exist, and one factor can influence others. To characterize such relations, the grey-DEMATEL approach has been utilized in this research. Grey-DEMATEL can capture the causal relations among supply chain risk factors. This method assists in information ambiguities and causal relation among risk factors for decision-makers.

2.3. Grey system theory and DEMATEL

Grey system theory and DEMATEL methods have been widely used in different sectors to solve decision-making problems. Golinska et al. (2015) proposed grey decisions making to classify the remanufacturing operations for identifying and prioritizing operations in the company. Rajesh and Ravi (2015) used Grey relational analysis to select the resilient supplier within a supply chain. Liu et al. (2017) utilized grey incidence analysis and grey clustering to identify the key indices in the remanufacturing industry in China. Mathivathanan et al. (2017) integrated grey relational analysis and an analytical hierarchy process to explore the impact of dynamic capabilities on the performance of sustainable supply chain firm.

Hsu et al. (2013) presented the DEMATEL method to develop a carbon management model for the green supply chain management supplier selection. Lin (2013) presented a fuzzy DEMATEL for the evaluation of green supply chain management practices. Gardas et al. (2018) used the DEMATEL approach for evaluating the critical, causal factors for post-harvest losses in the fruit and vegetables supply chain in India. Lin et al. (2018) identified the risk for new energy power system in China based on D numbers and DEMATEL method. Li and Mathiyazhagan (2018) applied the DEMATEL approach to identify the influential indicators towards sustainable supply chain adoption in the auto components manufacturing sector. Mavi and Standing (2018) combined fuzzy DEMATEL with analytic network process to recognize the critical success factors of sustainable project management in construction.

Recently, the integrated grey-DEMATEL method is gaining traction with researchers because of its capability to capture the interrelations among criteria. Xia et al. (2015) analyzed the internal barriers for automotive parts remanufacturers in China using grey-

Table 1
Some operational risks in food supply chains.

No.	Risk Types	Meaning	Sources
1	Supply	Suppliers fail to meet lead time or to provide good quality raw materials.	Guan et al. (2011)
2	Demand	Risk involved in demand fluctuations/demand uncertainty.	Guan et al. (2011)
3	Inventory	Inventory risk arises because of keeping too low or too high inventory.	Diabat et al., 2012; Liu and Fan (2011)
4	Detection of diseases in inputs	Diseases detection in input may hamper the quality of the products.	Assefa et al. (2017)
5	Lack of skilled personnel	Risks in executing business process or supply chains by unskilled persons.	Diabat et al., 2012; Jing et al. (2009)
6	Poor customer relationship	Risks resulting from poor customer relationship, which negatively impacts the business.	Assefa et al. (2017)
7	Unsafe and poor-quality products	Unreliable and defective products result a loss of reputation of the business.	Shirani and Demichela (2015); Sun (2014)
8	Failure in IT system	Disruption in business operations including sales, production, and cash flow in the supply chain because of IT system failure.	Diabat et al., 2012
9	Legal & regulatory	Failure to comply with laws and regulations imposed by government.	Jing et al. (2009); Sun (2014)
10	Capacity	Lack of capacity to produce quality products, or to meet customer demand. Absence of capacity flexibility, or capacity underutilization.	Jing et al. (2009); Orgut et al., 2016; Sun (2014)
11	Communication failure with supplier and bankruptcy of supplier	Communication failure with supplier may lead to delay payment. Also, suppliers may lose its existence due to various problems including bankruptcy.	Diabat et al., 2012
12	Change in customer taste and preferences	Failure to respond to ever changing consumer taste and preferences.	Diabat et al., 2012
13	Poor leadership	Risk in poor leadership, which hinders achieving enterprise and supply chain objectives.	Dani & Deep (2010)
14	Lack of Cooperation	Risk resulting due to the presence of cooperation risk. E.g. bullwhip effect.	Xiaoping (2016)
15	Machine/equipment failure	Production downtime due to failure of machine/equipment.	Jing et al. (2009); Shirani and Demichela (2015)
16	Environmental risk	Risk involved for a failure to meet environmental standard in food processing or preservation.	Dobler et al. (2014); Freise and Seuring (2015)
17	Disruption from man-made and natural disasters	Sudden risks can be happened due to man-made and natural disasters.	Govindan (2017); Xiaoping (2016)

Table 2
Summary of articles related to risk assessment in FSCs.

References	Method	Application
Nakandala et al. (2017)	Hierarchical holographic modeling and FL	To assess risk in FSCs
Song and Zhuang (2017)	Game theory	To model a government-manufacturer-farmer game for FSCs risk management
Xiaoping (2016)	Fuzzy AHP	To assess the safety risk in FSCs
Yongsheng & Xuan (2016)	Situational evaluation model	Factor analysis for FSCs risk
Shirani & Demichela (2015)	Failure modes and effects analysis	To assess risk in food production
Sun (2014)	Literature survey	Survey on risk assessment in FSCs
Diabat et al., 2012	Interpretive structural modeling	To investigate risks in FSCs
Wang et al. (2012)	Fuzzy set theory and AHP	To analyze safety risk in FSCs
Liu & Fan (2011)	System dynamics	To examine risk in FSCs
Guan et al. (2011)	Fuzzy AHP and fuzzy comprehensive evaluation	To investigate risks in FSCs

DEMATEL approach. Govindan et al. (2016) used grey-DEMATEL to find the interrelations among the risks faced by third-party logistics providers. Su et al. (2016) proposed the grey-DEMATEL structure to identify the aspects and criteria for supplier prioritization. Rajesh and Ravi (2017) employed grey-DEMATEL to assess drivers of risks in electronics supply chains. Wu et al. (2018) used grey-DEMATEL approach to identify and analyze the barriers to offshore wind power development in China.

2.4. Research gaps and highlights

FSCs are significant contributors to any nation's economy and are necessary for the well-being of the nation's citizens. Today's social consciousness has made managing FSCs both a significant local and global issue. Several ecent studies have focused on waste reduction and sustainability in FSCs. Gokarn and Kuthambalayan (2017) explored challenges that prevent food wastage reduction in the Indian agri-food supply chain using the interpretive structural model. Mangla et al. (2018) investigated key enablers to sustainable initiatives in the agri-food supply chain of India using the interpretive structural model and fuzzy-DEMATEL technique. Aimed to increase collaboration performance, Dania et al. (2018) systematically conducted a literature review to identify collaboration behavioral factors for implementing sustainable agri-food supply chains. Sharma et al. (2018) ranked key success factors to improve safety and security in sustainable FSCs. According to Corrado and Sala (2018), food waste is generated throughout the entire FSC and is dominated by different dynamics.

As noted, a research gap exists in investigating food supply chain risks and the dynamics or interactions among these risks Such investigations can guide managers in formulating risk and waste reduction strategies for actual industrial cases. This research uses a grey-DEMATEL framework for evaluating the contextual relationships among various risks in food supply chains. This research contributions include:

(i) Identifying various supply chain risks based on a literature review and experts' inputs.
(ii) Finalizing and evaluating supply chain risks and the contextual relations using a grey-DEMATEL framework.
(iii) Investigating cause and effect relations among the supply chain risks in the grey-DEMATEL framework.
(iv) Proposing managerial implications relating to issues of food wastage caused by the presence of risks in FSCs.

3. Methodology

The proposed research methodology is illustrated in Fig. 1. Following the brief discussion of grey theory and DEMATEL methods is the integrated grey-DEMATEL method that explores FSC risk relations. This integrated approach had the ability to capture causal relations between criteria (Chang et al., 2011) and to recognize the indirect and direct relations of several criteria (Rajesh and Ravi, 2017).

3.1. Identification of criteria for risk assessment

(a) Selection of risks in FSC

To identify and determining causal relations among the risks of FSCs, a survey was completed by food industry professionals and academic experts from Bangladesh. Initially, the questionnaires (see Appendix A) was sent to 164 experts by email to identify FSC risks. These experts were from the majority of the Bangladeshi food manufacturing and processing companies which are located in Dhaka (Tejgaon, Tongi, Savar, Narayanganj, Rupganj) and Chittagong (Kalurghat, Agrabad). The industry and respondents were chosen based on market share, product type, reputation, and experience. In this research, feedback was received from 130 respondents; 60 were from the supply chain department; 34, from the production department; 14, from logistics department; 12, from ICT department; and 10, from academic experts. The average working experience of the experts was 13.4 years in their respective position.

Initially, a Yes/No-based list of identified risks was provided to the decision-makers to identify the crucial risks in FSCs. Next, a 5-point Likert scale was given to the respondents to evaluate the importance of the risks. (See Appendix A). A Pareto analysis was performed to separate between the “useful many” and the “vital few” risks in FSC by prioritizing the occurrence frequency. Pareto analysis is widely used to identify the critical success factors in various fields such as in supply chain management, food safety assurance system, total quality management, and enterprise resource planning because of its easiness for implementation (Ab Talib et al., 2015; Bajaj et al., 2018). Managers and decision-makers often use Pareto analysis to direct focus to the major improvement opportunity by emphasizing the vital few causes or risks in contrast to the useful many (Bajaj et al., 2018). The Pareto chart from the 130 respondents is shown in Fig. 2. The average weight was considered for selecting the 10 most important FSC risks.

Among the 17 risks proposed in this research, the number of response values for the first two identified risks were 12 for disruption from man-made and natural disasters, and 12 for lack of skilled personnel. Similarly, the least important identified risks were a lack of cooperation and machine/equipment failure with the response values of 4 and 3, respectively.

(b) Identification of most important challenges

Based on the Pareto analysis, the 10 most crucial risks in the context of their FSC were analyzed further. These risks were disruption from man-made and natural disasters (R1), lack of

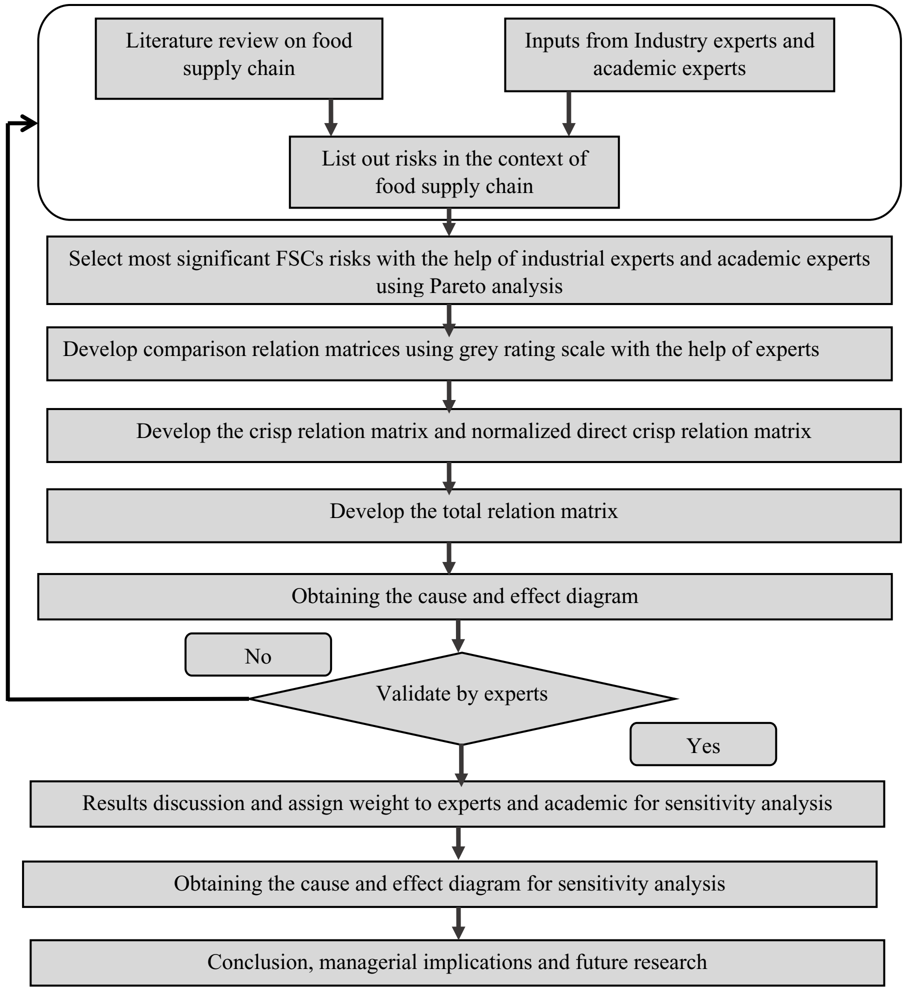

Fig. 1. Proposed grey-DEMATEL method for FSC risk assessment.

skilled personnel (R2), poor customer relationship (R3), unsafe and poor-quality products (R4), failure in IT system (R5), legal and regulatory (R6), capacity (R7), communication failure and bankruptcy of supplier (R8), change in customer taste and preferences (R9), and poor leadership (R10).

3.2. *Grey systems theory (GST)*

GST can be utilized to handle uncertainty in human or subjective judgment (Liu and Lin, 2011; Tseng, 2009). GST has an ability to handle incomplete and partial information (Julong, 1989).

The notation $\otimes P$ represents a grey number which can be marked as an interval with known lower limit value and upper limit value, but unknown distribution information for P (Julong, 1989). $\underline{P}$ and $\overline{P}$ represent the lower value and upper value of a grey number $\otimes P$, gradually which is expressed in the following equation (1) (Vafadarnikjoo et al., 2015):

$$\otimes P = [\underline{P}, \overline{P}] = \left[P' \in \otimes P \, \underline{P} \le P' \le \overline{P}\right] \quad (1)$$

The $\otimes P_{ij}^k$ is defined as the grey number for expert k, who will assess the impact of risk i on risk j. The notation $\underline{P}_{ij}^k$ and $\overline{P}_{ij}^k$ represent the lower and upper grey values of a grey number $\otimes P_{ij}^k$, consequently (Vafadarnikjoo et al., 2015). The equation for grey number $\otimes P_{ij}^k$ is expressed as,

$$\otimes P_{ij}^k = \left[\underline{P}_{ij}^k, \overline{P}_{ij}^k\right] \quad (2)$$

The three steps procedure of GST method follows:

Step 1: Normalization:

$$\tilde{\underline{P}}_{ij}^k = \left(\underline{P}_{ij}^k - \min_j \underline{P}_{ij}^k\right) \bullet / \bullet \Delta_{min}^{max} \quad (3)$$

$$\tilde{\overline{P}}_{ij}^k = \left(\overline{P}_{ij}^k - \min_j \overline{P}_{ij}^k\right) \bullet / \bullet \Delta_{min}^{max} \quad (4)$$

$$\Delta_{min}^{max} = \max_j \overline{P}_{ij}^k - \min_i \underline{P}_{ij}^k \quad (5)$$

Step 2: Calculation of total normalized crisp value:

$$Q_{ij}^k = \frac{\left(\tilde{\underline{P}}_{ij}^k \left(1 - \tilde{\underline{P}}_{ij}^k\right) + \left(\tilde{\overline{P}}_{ij}^k \times \tilde{\overline{P}}_{ij}^k\right)\right)}{\left(1 - \tilde{\underline{P}}_{ij}^k + \tilde{\overline{P}}_{ij}^k\right)} \quad (6)$$

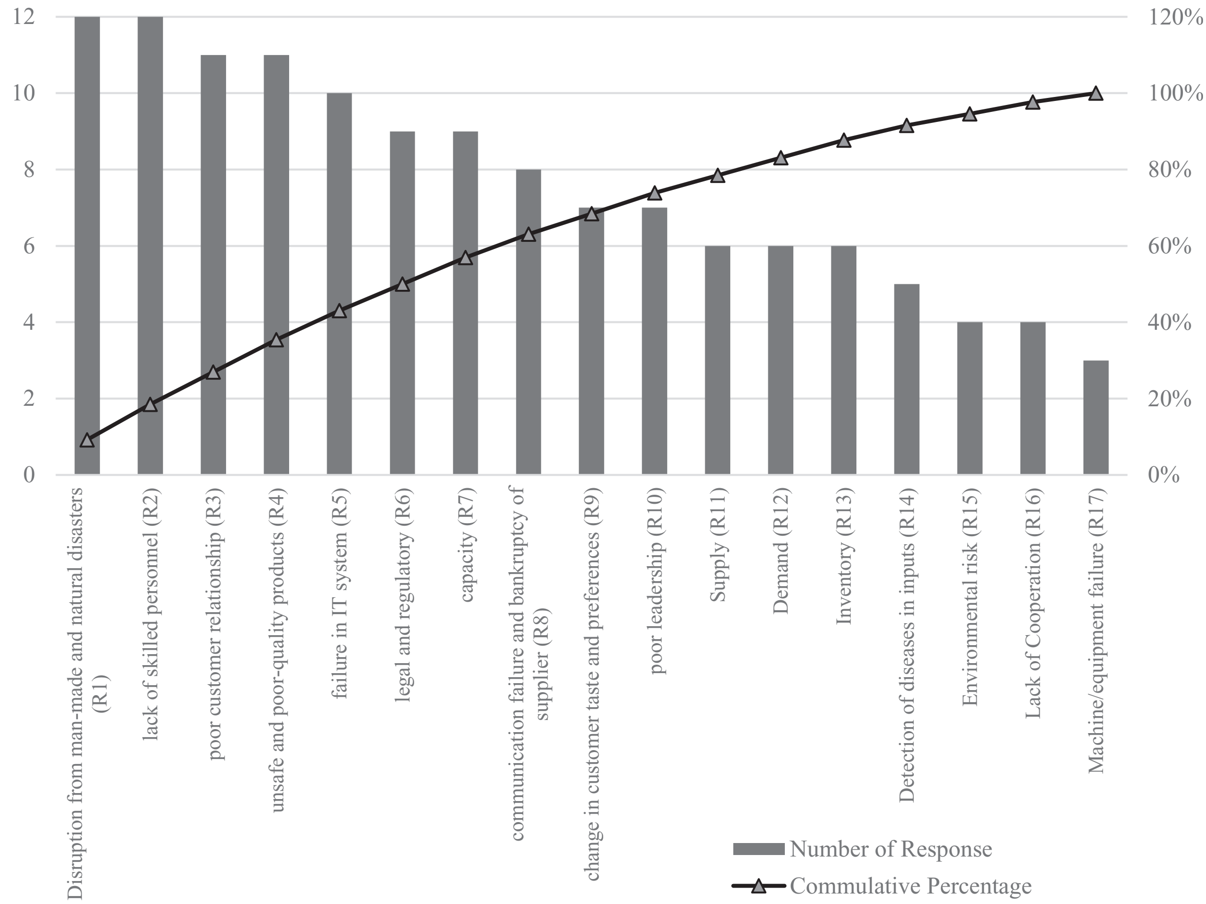

Fig. 2. Pareto chart of risks in FSCs.

Step 3: Calculation of crisp values:

$$R_{ij}^{k} = \underset{j}{min}\,\underline{\tilde{P}}_{ij}^{k} + Q_{ij}^{k}\Delta_{min}^{max} \tag{7}$$

3.3. DEMATEL methodology

DEMATEL is a technique which is originated from the Geneva Research Centre of the Battelle Memorial Institute (Fontela and Gabus, 1976). It is a structural model to compute the casual relationship between complicated factors (Chang et al., 2011). DEMATEL can be used to solve issues of dependency and complexity among criteria (Gabus and Fontela, 1972; Hsu et al., 2013). DEMATEL can categorize the total factors under investigation as either cause or effect groups.

The five steps procedure of DEMATEL methodology is explained below (Wang and Chuu, 2004):

1) *Obtaining the direct-relation matrices:* Five rating scales are employed to assess the relationship between factors. Five rating scale can be explained as follows: 0 means no influence, 1 means very low influence, 2 means low influence, 3 means high influence, and 4 means very high influence.

Industrial managers (experts) are recruited to construct pairwise comparisons matrices and as a result, for one industrial manager (expert), the matrix $A_{n\times n}$ (n indicates number of factors or criteria) will be produced. Each component of the matrix $A_{n\times n}$, which is presented by a_{ij}^{k}, is a number that indicates the influence degree of criteria i on j by industrial manager (expert) k. Using the following given equation, the average matrix for all expert opinions is formulated. In equation (12), H represents the number of experts and $\overline{a}_{ij}$ denotes each element of the average matrix

$$\overline{a}_{ij} = \frac{\sum_{k=1}^{H} a_{ij}^{k}}{H} \tag{8}$$

In DEMATEL technique, the obtained relationship between two factors/risks indicates how one factor/risk can influence other factor/risk. To represent the influences between factors/risks, values between 0 and 4 are utilized. The influence of factor/risk i on factor/risk j denotes how a decrease/increase in i can decrease/increase j.

2) *Normalization of the direct-relation matrix:* With the help of following equation, an initial average relation matrix is converted to a normalized matrix.

$$\mathrm{M} = \mathrm{k} \times \mathrm{A} \tag{9}$$

$$k = \frac{1}{max\sum_{j=1}^{n} a_{ij}} 1 \le i \le n \tag{10}$$

3) *Computing the total relation matrix:* In this step, with the help of following equation, the total relation matrix (T) is calculated:

$$T = M(I-M)^{-1} \tag{11}$$

Where, I represent an $n \times n$ identity matrix.

4) *Obtaining a cause–effect diagram:* D_i and R_j are denoted as a sum of row values and sum of column values, respectively, and it can be evaluated via using the following equations:

$$T = [t_{ij}]_{n\times n} \mathrm{i},\ \mathrm{j}\ =\ 1, 2,\ \&,\ \mathrm{n} \tag{12}$$

$$\mathrm{R_j} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n} = [t_{ij}]_{1\times n} \tag{13}$$

$$\mathrm{D_i} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} = [t_{ij}]_{n\times 1} \tag{14}$$

The prominence criterion is determined based on relative score of (D_i+ R_j). In the meantime, the relation vector ($D_i - R_j$) is also determined by subtracting R_j from D_i. Overall, a factor/risk will be a causal group factor/risk while the value of (D_i-R_j) is positive. If the value of (D_i-R_j) is negative, the corresponding factor/risk will be an effect group factor/risk.

5) *Acquiring the inner dependence matrix: After normalization process,* the summation of each column value in the total relation matrix will be 1. After that, the inner dependence matrix will be achieved.

3.4. Grey-DEMATEL method for FSC risk assessment

Step 1: Obtaining the direct-relation matrix

In this step, the pairwise comparison matrices are developed with the help of experts' opinions and using the five scales grey rating scale. To deal the ambiguity of human's subjective judgments, this study used linguistic rating scale based on grey numbers which is shown in Table 3. These grey numbers correspond to the influence scores of linguistic information. These grey values were converted to crisp values to utilize the DEMATEL techniques. This is performed using Equations (3)–(7).

Step 2: Changing the linguistic variable into grey linguistic scale for average grey relation matrix

Each evaluator (expert) provided an $n \times n$ linguistic direct-relation matrix for risks to assess the interrelationship among supply chain risk factors. With the assistance of Equation (8), the averages of experts' ratings are calculated to acquire the average grey relation matrix.

Step 3: Generating and obtaining the cause and effect diagram

With the help of Equations (9) and (10), the normalized initial direct-relation matrix (DRM) is computed. After that, the total relation matrix (TRM) is evaluated using Equation (11). Then, using Equations 12–14, the prominence and cause-effect group are constructed. Using the data set of (***D**$_i$*+ ***R**$_j$*, ***D**$_i$*-***R**$_j$*), the causal diagram is constructed.

4. Application of the proposed framework

The proposed model was used to investigated and assess the supply chain risk of a food processing company in Bangladesh. The case company, herein codenamed XYZ, is a leading food processing company in Bangladesh and started its operation in the year 1981 as processors of fruits and vegetables. This case company is one of the top-ranked food and beverage brands in the country and exports food products to 134 countries. Over the years, the company has not only produced food products but also largely contributed to the socio-economic development of Bangladesh. This company produces more than 400 products under 10 major categories like snacks, culinary, biscuits and dairy, juices, drinks, mineral water, bakery, carbonated beverages, and confectionery. This company is operated under ISO 9001 certification.

Table 3
Grey linguistic rating (Govindan et al., 2016).

Linguistic Variable	Influence Score	Grey numbers
No influence (No)	0	[0, 0]
Very low influence (VL)	1	[0, 0.25]
Low influence (L)	2	[0.25, 0.5]
High influence (H)	3	[0.5, 0.75]
Very high influence (VH)	4	[0.75, 1]

Recently, XYZ has faced supply chain risk challenges. The case company is committed to adopting the most suitable strategic policy to overcome the supply chain risk. Therefore, they want to find out the most significant FSC risks and want to know the interrelationship among them to improve its business efficiency in the market. The proposed grey-DEMATEL method is implemented to find out the interrelationship among FSC risk factors.

The data were collected through a secondary questionnaire (See Appendix B) from four experts using the five-point linguistic rating scale presented in Table 3. Three experts were chosen from the case company and one academic expert was selected based on their experience (highest years of experience) and intensity. Four respondents were selected based on purposive sampling techniques; where respondents selected based on many years of experience and intensity on this topic. During this process, the secondary questionnaire was completed using the one-to-one interview. Finally, the collected data and experts' opinions were examined using the developed grey-DEMATEL method. The procedure of the proposed model is described below:

4.1. Implication of Grey-DEMATEL method

Step 1: Constructing the direct-relation matrix

In this step, the assign experts were recruited to construct the relations between risks criteria considered. The five-point scale was used for the comparison. To deal with humans' subjective judgments, the grey numbers presented in Table 3 are used to formulate the DRM. Therefore, using the modified CFCS method, these grey numbers are converted to crisp values for employing the DEMATEL method.

Step 2: Changing the linguistic variable into grey linguistic scale for average grey relation matrix

To assess the interrelationship of each supply chain risk in the context of FSC, each expert formulated a 10 × 10 linguistic DRM. The averages of experts' opinions were computed based on Equation (8). The initial DRM obtained from Expert-1 is presented in Table C1 in Appendix C.

Step 3: Generating and obtaining the cause and effect diagram

The average grey relation matrix from direct grey relation matrices is computed by using Equation (8) and presented in Table C2.

To employee the DEMATEL methodology, using the modified

CFCS method and Equations 7–11, the average grey numbers are transformed to crisp values. Table C3 gives the obtained crisp value, which is provided in Appendix C. The normalized initial DRM was calculated using Equations 9 and 10. The TRM was calculated using Equation (11), which is shown in Table C4.

Finally, the ranking of prominence group and cause-effect groups were obtained using Equations 12–14. Tables 4 and 5 give the prominence vector and the relation vector, respectively.

5. Results and discussions

The causal diagram is constructed, and research findings are discussed as follows. According to the data set ($\boldsymbol{D_i}$-$\boldsymbol{R_j}$), lack of skilled personnel (R2), failure in IT system (R5), disruption from man-made and natural disasters (R1), legal and regulatory (R6), capacity (R7) are grouped into the cause category (Table 5). In the cause group, all five risks are very important for industrial managers for formulating risk mitigation strategies to minimize food wastage. Lack of skilled personnel takes the first position in the causal group, which indicates unskilled personnel are a burden and not effective to the company. Further, unskilled personnel may contribute to producing extensive wastage during the production process. Unskilled personnel can mistake to prepare the proper recipe for the food items which may produce the food wastage or food losses in the supply chains. This risk may count as one of the major risks for quality foods. Therefore, for the exports-oriented food items with improper quality which is supervised or prepared by unskilled personnel may produce food wastage greatly. Hence, skilled personnel is important to minimize risks in the food supply chain as well as to minimize food spoilage (Gustavsson et al., 2011; Papargyropoulou et al., 2014).

Failure in the IT system lies in disruption in the IT system may affect business operation including sales, production, and cash flow, and thus also needs greater priority in risk mitigation policy as well as to minimize wastage. Failure in the IT system can hamper the production system and thus will disrupt the production of required demand. The wrong signal from the IT system may contribute to producing excess production or the wrong recipe may produce food wastage. Due to the wrong IT signal, companies may produce an excessive quantity of food items respect to demand in the market which can impact in the profit margin of companies as well as can produce the food spoilage. Previous studies have given potential benefits of good structure IT system for packaging operation for food losses minimization (Williams et al., 2008). Therefore, the IT system is very important for reducing food wastage.

Disruption from man-made and natural disasters can hamper sales and promotion of foods. Man-made and natural disasters can also produce a huge wastage of food. Legal and regulatory risk indicates a failure to satisfy laws and regulation which can lead to damages, fines, and criminal sanctions against the company. Hence, if the companies produce a bad quality of food, then sometimes it may produce a large amount of waste during the investigation process by the legal authority.

Table 4
Prominence vector ($\boldsymbol{D_i}$+ $\boldsymbol{R_j}$).

Rank	Risk	D_i+ R_j
1	R10	5.0730
2	R5	4.2266
3	R4	4.0797
4	R2	4.0002
5	R7	3.8325
6	R3	3.5376
7	R8	2.4601
8	R9	2.2117
9	R1	1.2868
10	R6	1.0666

Table 5
Relation vector ($\boldsymbol{D_i}$-$\boldsymbol{R_j}$).

Rank	Cause group	D_i-R_j	Rank	Effect group	D_i-R_j
1	R2	1.5842	1	R3	−1.2661
2	R5	0.7488	2	R9	−1.0865
3	R1	0.3875	3	R10	−0.2639
4	R6	0.0348	4	R4	−0.1408
5	R7	0.0334	5	R8	−0.0314

Finally, the last risk in the causal group is capacity, which captures the risk associated with manufacturing production capacity, or the risk of producing low-quality foods. Capacity is also a relevant risk to produces food wastage. Low-quality food items may produce food spoilage which may come from a low production capacity of companies. During food processing various operations are involved like drying, sieving, milling grinding, mixing, cooking, molding, etc. which are directly or indirectly related to the production capacity of a company (Thi et al., 2015). For a smoother production system, the capacity should be high enough to minimize spoilage or food losses (Papargyropoulou et al., 2014). Therefore, the proper production facility and proper capacity is an important issue for the maximization of food industry profit and the minimization of food industry waste or losses.

The effect group is shown in Fig. 3, which includes poor customer relationship (R3), change in customer taste and preferences (R9), poor leadership (R10), unsafe and poor-quality products (R4), communication failure and bankruptcy of supplier (R8). In the effect group, these five risks also need greater attention from managers as they can be considerably influenced by the cause group risks. Poor customer relationship can negatively impact the business and affect obtaining pricing and competitive trade terms, and it gets the top priority in the effect group. In addition, the poor customer relationship may give an effect on food wastage. Food consumption is directly related to food spoilage because food consumptions depend on good customer relationship. Various studies have shown that poor consumers and producers may contribute to producing food spoilage (Gustavsson et al., 2011; Hodges et al., 2011). The previous studies stated that in developed countries 40% of food wastage occurred in food consumptions stage (Gustavsson et al., 2011). Change in customer taste means consumers' taste, preferences continuously changing and failure in responding to that change. Poor demand for changes in customer taste on particular food items may also produce food wastages.

Poor leadership can hinder obtaining risk management goals. The unsafe and poor-quality product produced by the manufacturing process is due to many reasons, including human error or machine/equipment failure can reduce the brand image. Finally, in the effect group, communication failure with the supplier and bankruptcy of supplier gets the last position in the effect group, which means this risk can be considered as a cause risk. This risk refers to late payment to the supplier, or faulty, late, or undelivered goods and suppliers internal problems. Products evaluation during quality checkpoint and the standard recipe are directly or indirectly related to good leadership. Therefore, poor leadership may produce huge food spoilage due to quality or proper recipe issues (Papargyropoulou et al., 2014). From the food processing to food marketing all depend on good leadership. If the leadership is good then the food wastage will be minimized or vice versa (Parfitt et al., 2010). All these effect FSCs risks in the effect group are influenced by the cause group FSCs risks.

The ($\boldsymbol{D_i}$+ $\boldsymbol{R_j}$) scores represent the relative importance of each FSCs risk; as a result, the higher score of ($\boldsymbol{D_i}$+ $\boldsymbol{R_j}$) may get the

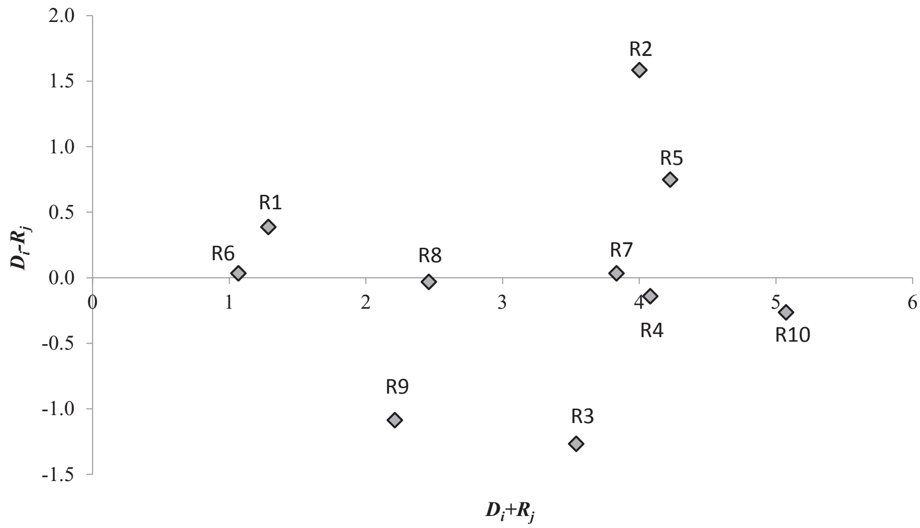

Fig. 3. Cause and effect diagram of FSC risk evaluation.

highest priority in the risk ranking process. Poor leadership (R10) enjoys the maximum (D_i+ R_j) value (Table 4). Cause criteria can influence other effect group criteria in the system, thus affecting the overall performance of the system.

Due to the positive score of (D_i+ R_j), the causal group of FSCs risks gets the significant attention in the decision-making process, and it indicates that the score of influential impact (D_i) is higher than the score of influenced impact (R_j). The lack of skilled personnel (R2) in the cause group gets the first rank with a score of 1.5842 (Table 5). In the context of the Bangladeshi food processing company supply chain, unskilled personnel can increase the operational risks because the quality of food is largely dependent on skilled personnel. So, the manager should pay attention to this risk during adopting a strategic policy for minimizing risk occurring in an FSC.

According to the data set (D_i+ R_j), poor leadership (R10), failure in the IT system (R5), unsafe and poor-quality products (R4), lack of skilled personnel (R2), and capacity (R7) are all important risks (Table 4).

According to the (D_i+ R_j) score, only the lack of skilled personnel (R2) and failure in the IT system (R5) are in the cause group among the five most important risks. Thus, lack of skilled personnel (R2) is preferred to failure in the IT system (R5) because they rank first and second in (Di − Rj) ranking and fourth and second in (D_i+ R_j) ranking, respectively, and as can be seen the priority of (R2) in (D_i- R_j) ranking is much greater than the priority of (R5) in (D_i+ R_j) ranking. As a result, examining both the prominence group (Table 4) and the cause group (Table 5) ranking with more accentuation on the cause group, the most significant risk of risk assessment is lack of skilled personnel (R2), poor leadership (R10), and failure in the IT system (R5), poor customer relationship (R3), and capacity (R7). Based on the analysis of the 10 risks, the most important risks are presented in Table 6.

The specific quantitative understanding of risks may offer some managerial insights to decision-makers to reduce food wastage. In this study, some risk mitigation strategies to these important supply chain risks are proposed. The study reveals that the lack of skilled personnel received the highest priority in the causal group. This finding offers significant insights for decision-makers to make the FSC network risk free and sustainable. In addition, to minimize food wastage, skilled personnel may contribute a huge impact on FSCs. Industrial decision-makers will be able to understand the relative importance of this finding and thus will greatly suggest formulating a training program for developing skills of personnel to minimize the food waste significantly. Poor leadership also plays a critical role in the risks in FSC. Industrial decision-makers should give the insight to formulate strategic policy regarding legal and regulatory rules to minimize the risks and eliminate the effect group risks for the FSCs. This will help decision-makers to make FSCs more sustainable and efficient. Further, decision-makers will be able to realize the importance of legal and regulatory rules for food wastage minimization. As a failure in the IT system received the third highest weight in the causal group. It suggests that decision-makers give proper attention to the IT system because developing IT infrastructure will help minimize the operational risk as well as help to minimize food wastage in the FSCs.

The risk 'capacity' should be optimal to meet customer demand. Hereafter, decision-makers should enhance the capacity to eradicate the effect group risks simultaneously. To deal with the poor customer relationship risk, the organizations can develop a proper database based on the customers' needs and expectations. The risk 'Disruption from man-made and natural disasters' can be minimized via adopting proactive and reactive strategies. Hence, this risk can impose great influence on effect group risks. This finding suggests decision-makers be more conscious of it during developing a risk mitigation strategy to reduce food wastage.

This research has identified five risks as the most significant, which are a lack of skilled personnel, poor leadership, failure in the IT system, capacity, and poor customer relationship. The findings of this research deviate significantly from supply chain risks prioritization in other industrial sectors. Considering Moktadir et al. (2018a) have identified and analyzed supply chain risks in the pharmaceutical industry, and have found that machine, equipment, or facility failure, fluctuation in imports arrival, quality risks, non-availability of materials, and demand forecasting errors are the top supply chain risks in the pharmaceutical industry. Prakash et al. (2018) have assessed risks in the automobile supply chain. They have concluded that demand risks, process risks, and supply risks are the most dominant in the automobile supply chain. Honarvar et al. (2013) explored supply chain risk in a petrochemical company of China and found that political factor is the main factor causing supply chain disruptions. Diabat et al. (2012) suggested that Indian food supply chain managers should give high priority to product/service management risks.

The top risks found in this study have significant implications for reducing waste and optimizing resources in food supply chains.

Table 6
Five most important risks, their rankings, and mitigation strategies.

Risk	Cause group rank	Prominence rank	Final rank	Mitigation Strategies
Lack of skilled personnel (R2)	1	4	1	Continuous training and development
Poor leadership (R10)	NA	1	2	Leadership training, including supply chain leadership
Failure in IT system (R5)	2	2	3	Identify vulnerability in IT system and take proactive and reactive measures
Capacity (R7)	5	5	4	Better planning and capacity flexibility
Poor customer relationship (R3)	NA	6	5	Building big data on customers and their needs and expectations

Note: NA means the risk belongs to effect to group, thus no ranking in the cause group.

Making workers and managers skilled and knowledgeable about loss and waste reduction practices across the food supply chain can help in reducing food waste throughout the supply chain. Supply chain knowledge sharing is important in achieving food supply chain objectives in an emerging economy like Bangladesh. For reducing food waste and ensuring food safety, quality leadership and supply chain leadership can play a significant role. Quality leadership and supply chain leadership are critical for effective food quality management implementation process across the food supply chain.

Supply chain partners are benefited through cooperation and information sharing, which stresses the significance of communication and IT-enabled system for managing supply chains (Soroor et al., 2009). Failure in the IT system may result in poor decision making, for example, inventory replenishment and capacity activation decision, which may induce resource wastage in the supply chain. Capacity risk, one of the important risks in the food supply chain, may contribute to producing defective products and resource wastage. Further, the absence of capacity flexibility or capacity underutilization is also crucial for the loss of resources in the food supply chain. Finally, maintaining strong relationships with customers is a key driver for achieving commercial sustainability in the food supply chain. Thus, the poor customer relationship is a threatening factor to sustain local and global competition and can result in the loss of resources and food waste across the food supply chain.

5.1. Sensitivity analysis

Sensitivity analysis of the proposed grey-DEMATEL method is carried out to check the robustness of the obtained result and to justify the robustness of experts opinion. In this study, four iterations are carried out by giving different weights to Expert-1 because Expert-1 is more important than other experts. The different weights assigned to experts are shown in Table 7. The same weight is assigned to experts in the previous section for carrying out a ranking of FSC risks. Similarly, different weight combinations or different iterations can be observed to expand the sensitivity analysis.

To find out the cause-effect relationship among multiple risks, at the initial stage, a weighted average matrix is computed, which is used as a DRM. The rest of the procedure is explained in the methodology section. In iteration-1, 2, 3, and 4, there is no change in the ranking with respect to ($\boldsymbol{D_i}+\boldsymbol{R_j}$) (Fig. 4, D1-D2). This indicates that the result is consistent with respect to four experts.

The risks R3, R9, R10, R4, and R8 are shown as the same ranking in the effect group (in ($\boldsymbol{D_i}$-$\boldsymbol{Rj}$) ranking) with respect to iteration-1 and 2. Hence, in iteration-3 and 4, another risk is included in this group and that risk is R6. A small ranking variation occurred in the case of iteration-3 and 4. Therefore, it is clear from the obtained Figs. 3 and 4, D1-D2 that the five most important risks are not sensitive during weights variation from Expert-1. Hence, the sensitivity analysis proved that the obtained result is stable.

6. Conclusions

In this study, an integrated grey-DEMATEL method is developed to determine the causal relationship between the identified risks. This research makes a significant contribution to the case of FSC risk management and for developing risk mitigation strategies to reduce food wastage. The finding determined the structure and interrelationship among the risks for an FSC. The findings revealed that five risks were obtained as causal risks whereas five risks were obtained as effect risks. It was also clear from the findings that lack of skilled personnel took the first position in the causal group, which can hamper the sustainable production system. This risk has a significant impact on food waste generation in the FSC. Consequently, capacity was ranked as last in the causal group, which had to have a strong contribution to food wastage. On the other hand, in the effect group, poor customer relationship received the first priority in the ranking, which can also act as a causal risk. Therefore, the results indicate that "lack of skilled personnel" is the most important risk for the supply chain. Other important risks are poor leadership, failure in the IT system, capacity, and poor customer relationship. The findings showed that the lack of skilled personnel has the highest influence on the risks. The results are useful for food industries to identify supply chain risks. In addition, the result assists the food industry in reducing cost, concentrating on developing proficiency and lowering risks in the FSC.

All these managerial insights on causal group risks will help to eradicate effect group risks simultaneously. Further, ultimately developing strategic decisions may help decision-makers to minimize all risks as well as to reduce food wastage. The proposed grey-DEMATEL model can be applied to for examining the interactions among supply chain risks, which can guide managers in risk-based and informed decision making to make the supply chain more resilient and secured. The proposed model can be used to assess the supply chain risk of other industries like apparel, pharmaceutical, furniture, leather, footwear, polymer, and develop a comprehensive framework for the collaboration of experts from different

Table 7
Important weights assign to experts for sensitivity analysis.

Experts	Iteration-1	Iteration-2	Iteration-3	Iteration-4
Expert-1 (Supply chain dept.)	0.1	0.5	5	7
Expert-2 (Production dept.)	1	1	1	1
Expert-3 (Logistics dept.)	1	1	1	1
Academic-1 (Supply chain management)	1	1	1	1

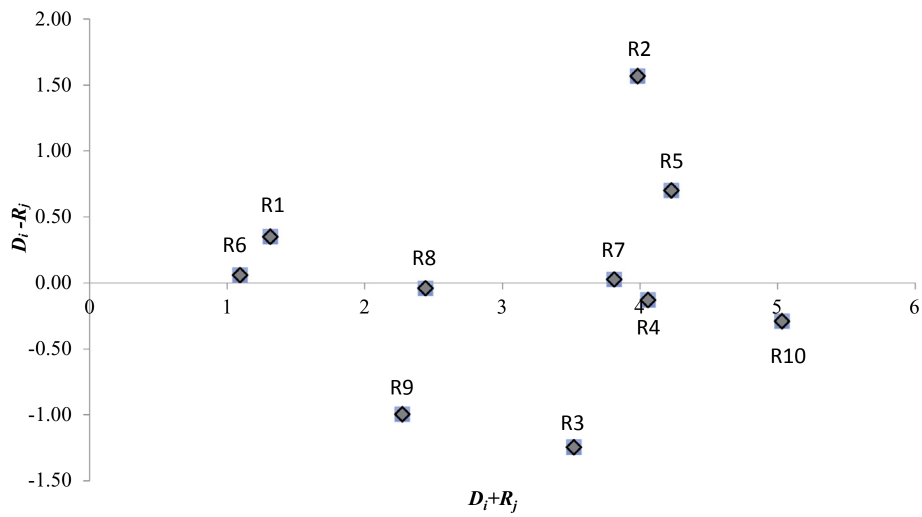

Fig. 4. Cause effect relationship among risks at iterations 1 & 2.

disciplines of knowledge.

A generic grey-DEMATEL model is presented for risk assessment in food supply chains. As food waste is resulting throughout the entire food supply chain around the world, improving the local food supply chain can contribute to optimization of the food supply chains at the global scale (Corrado and Sala, 2018). In this research, a food supply chain case from Bangladesh is selected deliberately to test the model. The model would work for other countries' food supply chain as well. This model is also expected to be applicable and beneficial to any country context for improving the food supply chain. In addition, this proposed model can be implemented in other industrial domains of other regions. To do this, at first managers' feedback on supply chain risks on a specific industry can be collected by distributing the list of supply chain risks, identified in this paper, to the supply chain partners and managers of the industry. Then, a Pareto analysis can be performed to find out the most important risks related to the industry. Finally, using the grey-DEMATEL method, managers can find the cause-effect relationships among the identified risks for the policy-making towards waste minimizations across the supply chain. However, the application of the model in a different context will generate a different outcome because every supply chain is characterized by the economic, social, political, natural, and geographic factor in which the supply chain is operating (Christopher and Peck, 2004).

The proposed model can be linked with the Internet of Things (IoT) which can help to monitor, control, plan, and optimize supply chains in real time. Linking IoT to grey-DEMATEL may deal with unpredictable supply chain risks and disruptions. The sustainability risk can also be included in FSCs as it is an important topic of discussion in both academia and industry. The research can be further extended and validated using business data analytics (Wu and Huang, 2018) or other hybrid MCDM methods such as a grey-based interpretive structural model or grey-based analytic network process.

Appendix A

Primary Questionnaires

1. Please answer the following queries:
   a) Name:
   b) Name of the companies:
   c) Types of the products:
   d) Role:
   e) Years of experience:
2. Selection of FSCs risks: Please select the most important FSCs risks from the following

No.	Risk Types	Yes/No	5: highly important and 1: very weakly important				
			5	4	3	2	1
1	Supply						
2	Demand						
3	Inventory						
4	Detection of diseases in inputs						
5	Lack of skilled personnel						
6	Poor customer relationship						
7	Unsafe and poor-quality products						
8	Failure in IT system						
9	Legal & regulatory						
10	Capacity						
11	Communication failure with supplier and bankruptcy of supplier						
12	Change in customer taste and preferences						
13	Poor leadership						
14	Lack of Cooperation						
15	Machine/equipment failure						
16	Environmental risk						
17	Disruption from man-made and natural disasters						

Appendix B

Secondary Questionnaire

Finding the casual relationship among the identified risks in FSCs.

List of Identified Risks	Code
Disruption from man-made and natural disasters	R1
Lack of skilled personnel	R2
Poor customer relationship	R3
Unsafe and poor-quality products	R4
Failure in IT system	R5
Legal and regulatory	R6
Capacity	R7
Communication failure and bankruptcy of supplier	R8
Change in customer taste and preferences	R9
Poor leadership	R10

Table B1
Direct relation matrix (Name of the experts)
Please provide your opinion based on given scale (0: No influence (NO), 1: Very low influence (VL), 2: Low influence (L), 3: High influence (H), and 4: Very high influence (VH)).

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R1	0									
R2		0								
R3			0							
R4				0						
R5					0					
R6						0				
R7							0			
R8								0		
R9									0	
R10										0

Appendix C

Table C1
Direct relation matrix (Expert-1).

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R1	0	1	0	1	2	3	0	2	0	1
R2	1	0	3	3	3	2	4	1	0	3
R3	0	1	0	1	2	0	0	1	3	3
R4	0	2	2	0	1	0	3	2	4	3
R5	0	2	3	2	0	1	3	3	2	4
R6	1	1	0	0	1	0	0	1	1	2
R7	0	1	3	4	2	0	0	1	2	3
R8	2	0	1	3	2	0	1	0	0	2
R9	0	0	2	1	1	0	0	0	0	1
R10	1	3	4	3	2	1	3	2	1	0

Table C2
Average grey relation matrix.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R1	0, 0	0, 0.25	0, 0	0, 0.25	0.25, 0.5	0.5, 0.75	0, 0	0.25, 0.5	0, 0	0, 0.25
R2	0.0625, 0.3125	0, 0	0.5, 0.75	0.5, 0.75	0.5, 0.75	0.25, 0.5	0.75, 1	0, 0.25	0, 0.0625	0.5, 0.75
R3	0, 0	0, 0.25	0, 0	0, 0.25	0.25, 0.5	0, 0	0, 0.125	0, 0.25	0.5, 0.75	0.5, 0.75
R4	0, 0.0625	0.25, 0.5	0.25, 0.5	0, 0	0, 0.25	0, 0	0.5, 0.75	0.25, 0.5	0.75, 1	0.5, 0.75
R5	0, 0	0.25, 0.5	0.5, 0.75	0.25, 0.5	0, 0	0, 0.25	0.5, 0.75	0.5, 0.75	0.25, 0.5	0.75, 1
R6	0, 0.25	0.0625, 0.3125	0.0625, 0.125	0, 0	0, 0.25	0, 0	0, 0.0625	0, 0.25	0, 0.25	0.25, 0.5
R7	0, 0.0625	0, 0.25	0.5, 0.75	0.75, 1	0.25, 0.5	0, 0	0, 0	0, 0.25	0.25, 0.5	0.5, 0.75
R8	0.25, 0.5	0, 0	0, 0.25	0.5, 0.75	0.25, 0.5	0, 0	0, 0.25	0, 0	0, 0	0.25, 0.5
R9	0.0625, 0.125	0, 0.0625	0.25, 0.5	0, 0.25	0.1875, 0.4375	0, 0	0, 0	0, 0	0, 0	0.0625, 0.3125
R10	0, 0.25	0.5, 0.75	0.6875, 0.9375	0.5, 0.75	0.25, 0.5	0, 0.25	0.5, 0.75	0.25, 0.5	0, 0.25	0, 0

Table C3
Crisp relation matrix.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R1	0	0.063	0	0.050	0.375	0.688	0	0.375	0	0.050
R2	0.185	0	0.707	0.700	0.729	0.417	0.988	0.063	0.004	0.700
R3	0	0.063	0	0.050	0.375	0	0.014	0.063	0.650	0.650
R4	0.007	0.375	0.355	0	0.063	0	0.650	0.375	0.950	0.650
R5	0	0.375	0.658	0.350	0	0.063	0.650	0.688	0.350	0.950
R6	0.083	0.141	0.070	0	0	0	0.004	0.063	0.050	0.350
R7	0.007	0.063	0.658	0.950	0.375	0	0	0.063	0.350	0.650
R8	0.417	0	0.053	0.650	0.375	0	0	0	0	0.350
R9	0.076	0.005	0.355	0.050	0.297	0	0	0	0	0.125
R10	0.083	0.688	0.885	0.650	0.375	0.063	0.650	0.375	0.050	0

Table C4
Total relation matrix.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R1	0.0196	0.0536	0.0690	0.0757	0.1294	0.1642	0.0577	0.1244	0.0436	0.1001
R2	0.0780	0.1494	0.4365	0.3944	0.3388	0.1297	0.4290	0.1598	0.2140	0.4625
R3	0.0189	0.0787	0.1254	0.1072	0.1590	0.0159	0.0965	0.0742	0.2085	0.2513
R4	0.0370	0.1729	0.2800	0.1790	0.1586	0.0286	0.2831	0.1646	0.3285	0.3372
R5	0.0476	0.2076	0.3929	0.3072	0.1800	0.0494	0.3320	0.2625	0.2455	0.4630
R6	0.0286	0.0627	0.0747	0.0513	0.0550	0.0128	0.0496	0.0427	0.0426	0.1306
R7	0.0290	0.1225	0.3366	0.3546	0.2069	0.0235	0.1610	0.1157	0.2346	0.3486
R8	0.1090	0.0698	0.1298	0.2359	0.1573	0.0282	0.1141	0.0746	0.0925	0.2033
R9	0.0241	0.0312	0.1316	0.0534	0.1019	0.0093	0.0434	0.0328	0.0428	0.0921
R10	0.0579	0.2596	0.4252	0.3515	0.2520	0.0543	0.3332	0.1945	0.1965	0.2799

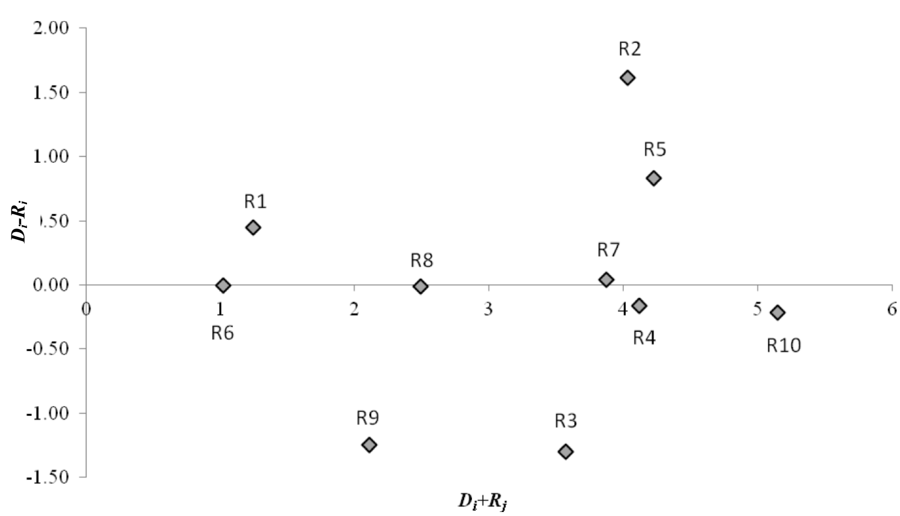

Fig. D1. Cause effect relationship among risks at iteration-3.

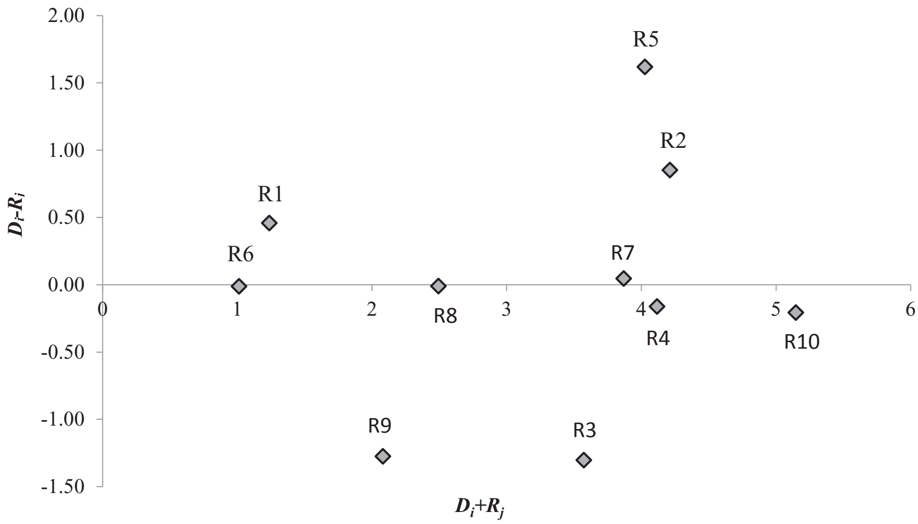

Fig. D2. Cause effect relationship among risks at iteration-4.

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