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Analysis of Factors in Food Security by Neutrosophic Fuzzy Set with DEMATEL

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ABSTRACT

Food Security (FdS) is critical for sustainable development, poverty reduction and social stability. The United Nations' Sustainable Development Goal (SDG) 2, Zero Hunger, aims to "end hunger, achieve food security and improved nutrition, promote sustainable agriculture" by 2030. Despite huge efforts and extensive research having been carried out to study the factors of FdS, the practices on improving the precision and accuracy have seemed absent in these studies. Thus, this study presents an integrated approach combining Neutrosophic Set (NS) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to analyse the interrelationship among eight key factors affecting FdS. The aggregated values for the Decision Makers' (DMs) evaluation were computed using the arithmetic mean. Subsequently, DEMATEL was applied to determine the causal relationships and the degree of prominence of the eight factors studied. The findings reveal that the factors such as Climate Patterns, Economic Access and Resilience to Shocks and Crises have a significant influence on the stability and sustainability of food systems. The proposed framework effectively handles uncertainty and interdependencies in Multi-Criteria Decision-Making (MCDM), offering valuable insights for policymakers and stakeholders, who aim to enhance FdS strategies. This study has demonstrated the advantage of integrating Neutrosophic fuzzy set with DEMATEL in addressing the complexity of the MCDM process.

1. Introduction

1.1 Research Background

Fuzzy set (FS) theory is a mathematical way to represent vague or inaccurate information by assigning a degree of membership from 0 to 1 for elements in a set. It means, FS allows to handle uncertainty and reasoning which permit gradual membership of elements in sets rather than classical "Yes" or "No". FS theory was proposed by Lofti Zadeh [1] to extend classical (crisp) set theory. FS is often applied in areas such as Artificial Intelligence (AI) that were conducted by Habib and Hwang [2], control systems that were conducted by Liu *et al.*, [3], decision making that were conducted by Ali *et*

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al., [4] and pattern recognition which were conducted by Zhu *et al.*, [5], where obtaining precise knowledge is more difficult. Neutrosophic set (NS), which was introduced by Florentin Smarandache in 1995, focus on studying neutralities, nature, origins and their interactions across domains, with elements represented by Truth (T), Indeterminacy (I), and Falsity (F) within the range [0,1] [6].

In the past few years, the application of FS theory such as NS, Interval-Valued Fuzzy Set (IVFS) and Intuitionistic Fuzzy Set (IFS) had been used in the analysis of factors of a certain field. For example, NS had been used in studying various factors in logistics by Kaspar and Palanivel [7], while IVFS had been used in constructing variable-granularity distance measure, that were conducted by Wang & Zhang [8] and an evaluation of a medical oxygen supply system had been successfully carried out by implementing IFS, that were conducted by Yousofnejad and Es'haghi [9]. The application of FS theory enabling the Decision Makers (DMs) to make suitable decision based on the results of the analysis of the factors using the FS. Arithmetic Mean, combining with the arithmetic operations of NS will be used to aggregate the data from DMs' evaluation, capturing the central tendencies among the values.

Moreover, the aggregated results will then be analysed using the Decision-Making Trial and Evaluation Laboratory (DEMATEL), a Multi-Criteria Decision Making (MCDM) method that is used to visualize and analyse complex decision-making problems, especially when dealing with interrelationships between factors. It is particularly effective in identifying cause-effect relationships and prioritizing factors that influence a system. This can be seen in the existing research paper where DEMATEL is powerful in analysing cause and effect in small and micro enterprises that were conducted by Deetae *et al*., [10] and hydrogen-fueled logistics which were conducted by Niemsakul *et al*., [11]. The combined approach of NS and DEMATEL will be used to study the factors that impact Food Security (FdS).

According to the definition adopted by the World Food Summit (1996) in World Bank Group [12], FdS exists when every person, at every moment, has physical and economic access to enough safe and healthy food that is needed in terms of their specific dietary requirements and food choices for healthy and active living. The four key aspects in FdS, namely physical availability, that ensures that a nation's total food production, reserves, and imports meet population needs, economic and physical access to food, which determined by the household income, local food prices and transportation network, food utilization, that reflected by the nutrition and healthcare education and the stability, where the interaction of the other three aspects is significant to the stability and sustainability of FdS. For physical availability of food, this is a measure of FdS that looks at the "demand side" and is influenced by the amount of food produced, the amount of food stored, and the amount of food imported or exported.

Besides, the second aspect of FdS is economic and physical access to food. Having an adequate supply of food either at country level or international level is not sufficient to ensure FdS at household level. The presence of FdS challenges has shifted the focus of attention in policy strategies designed towards FdS from food availability to incomes, expenditures, markets, and prices.

In terms of food utilization, this is usually understood as how much and in what way the body uses the different nutrition in the food consumed. Sufficient energy and nutrients consumed by people depend on proper care and feeding, food cooking and the variety in the meal, and sharing of food within the household.

The fourth aspect in FdS is the stability of the other three dimensions over time. Although one may claim that the FdS is stable, however food insecurity could be happening if one having inadequate and unstable access to food on a periodic basis, which will risking the nutritional wellbeing. Various factors such as critical climate change, politics instability or economic factors can greatly impact FdS status. For example, the Covid-19 pandemic during December 2019 had a significant impact on FdS, where economics were drastically weakened and threatened FdS in society.

This led to malnutrition and increased mortality in the communities. Thus, it is necessary that all the four elements are met at the same time to achieve the FdS objectives.

In addition, the study of factors of FdS is important to secure a multidimensional access to food resources in vulnerable populations and identify patterns and relationships that can help in implementing more effective public policies and interventions strategies to improve FdS, which were conducted and concluded by Raffo-Babici *et al*., [13]. Also, the study of FdS helps in the evolution of FdS in adapting variable dimensions such as climate change, availability and economics which was conducted by Li [14].

This study is conducted to identify the potential factors that affect the four aspects of FdS using fuzzy set theory logic. Analysis of the tiering levels of the factors studied enables suitable methods or solutions to be proposed to tackle the problem.

1.2 Literature Review

For NS, it generalizes FS theory with three independent degrees: truth, falsity, and indeterminacy. There are three independent values, Truth (T), Falsity(F) and Indeterminacy (I), with each ranging independently from 0 to 1. NS handles uncertainty more broadly with independent values for truth, falsity, and indeterminacy, accommodating conflicting information. NS can be applied in domains such as decision making which were conducted by Kamran *et al*., [15] and stability analysis that were conducted by Acharya *et al*., [16] to address situations where information cannot be easily represented using traditional binary logic and thus allowing for better representation of uncertainty and contradictions.

On the other hand, DEMATEL is a MCDM method for identifying and examining cause-effect relationships in complex systems, as suggested by Dang *et al*., [17]. DEMATEL arranges the factors into cause-and-effect relationships by assessing how each affects the others, offering insight into how they interact. It produces a matrix that illustrates the strength and direction of these influences through pairwise comparisons, which can subsequently be displayed on a map. This aids DM in determining the most important components of a system and comprehending how they affect other components.

DEMATEL had been used in the analysis of quality control criteria in a glass business, which able to increase the customer satisfaction and improve competitive advantages in the industry, that were conducted by Çelik and Arslankaya [18]. A causal model in green supply chain management for strategic environmental practices was developed and able to improve the performance of green supply chain management by identifying the net causer and net receiver by using the DEMATEL method, which were conducted by Mohamed *et al*., [19].

The combination of NS and DEMATEL seemed to be useful in the searching of a comprehensive solution that was used to propose a leanness assessment methodology which able to help a company's lean transformation, that were conducted by Kilic *et al*., [20]. Cognitive mapping, which was applied by a panel of experts in urban renewal planning, can be completed by implementing the combination of NS and DEMATEL, that were conducted by Cordeiro *et al*., [21].

Furthermore, FdS ensures a continued focus on FdS corresponding to the growth of the population and increasing nutritional demands, as what was embedded in the second Sustainable Development Goal (SDG) of Zero Hunger as discussed by Xu *et al*., [22]. The growing of the human population or urbanization has gradually impacted on FdS, which demands various dietary and nutrition, to provide balanced diet to the community. Moreover, climate change, that were conducted by Lara-Arévalo *et al.*, [23] and the outbreak of viruses, which were conducted by Rudin-

Rush *et al.*, [24], are some of the verified challenges and factors that affect the balance of FdS. Therefore, it is important to identify more potential factors that can affect the stability of FdS.

2. Methodology

2.1 Neutrosophic Set

NS emphasizes the study of neutralities, their nature, origins and the interactions across domains. The elements are characterized by three components, namely Truth (T), Indeterminacy (I), and Falsity (F), with each taking values within the range of [0,1]. The word "Neutrosophy" is a combination of word "neutral" and the Greek word "sophia" (wisdom), which gives the meaning of "the knowledge of neutral thought".

NS, A in the universe U is of the form

$$A = \{(x, T_A(x), I_A(x), F_A(x)): x \in U, T_A(x), I_A(x), F_A(x) \in [0,1]\} \tag{1}$$

In the equation Eq. (1), $T(x)$, $I(x)$, and $F(x)$ are the degree of Truth, Indeterminacy and Falsity of x in A respectively, which can be called as neutrosophic components of x. If the sum of $T(x)$, $I(x)$, and $F(x)$ is between 0 and 3, the set can be called a single-valued neutrosophic set (SVNS). For simplicity, a single-valued neutrosophic number (SVNN) $(\alpha, T_A(\alpha), I_A(\alpha), F_A(\alpha))$ in A can be denoted as $\alpha = (\alpha_T, \alpha_I, \alpha_F)$, where $\alpha_T, \alpha_I, \alpha_F \in [0,1]$ and $0 \le \alpha_T + \alpha_I + \alpha_F \le 3$., as discussed by Zhang *et al.*, [25].

2.1.2 Arithmetic operations of neutrosophic set

The basic operations of two SVNN, $A = (\alpha_T, \alpha_I, \alpha_F)$ and $B = (\beta_T, \beta_I, \beta_F)$, as discussed by Zhang *et al.*, [25] are defined as follows

(i) Complement of A

$$A^c = (\alpha_T, 1 - \alpha_I, \alpha_F) \tag{2}$$

(ii) Addition of A and B

$$A \oplus B = (\alpha_T + \beta_T - \alpha_T\beta_T, \alpha_I\beta_I, \alpha_F\beta_F) \tag{3}$$

(iii) Multiplication of A and B

$$A \otimes B = (\alpha_T\beta_T, \alpha_I + \beta_I - \alpha_I\beta_I, \alpha_F + \beta_F - \alpha_F\beta_F) \tag{4}$$

(iv) Scalar Multiplication of A, $\lambda \in \mathbb{R}$

$$\lambda A = \left(1 - (1 - \alpha_T)^\lambda, \alpha_I^\lambda, \alpha_F^\lambda\right) \tag{5}$$

(v) Power of A, $k \in \mathbb{R}$

$$A^k = \left(\alpha_T^k, 1 - (1 - \alpha_I)^k, 1 - (1 - \alpha_F)^k\right) \tag{6}$$

2.1.3 The arithmetic mean combining arithmetic operations of NS

While ordinary Arithmetic Mean is mentioned, the aggregation process should combine with the arithmetic properties of NS, as discussed in section 2.1.2.

As there are total of three DMs ($n = 3$) in this study, the addition and multiplication processes for three SVNN, $A = (\alpha_T, \alpha_I, \alpha_F), B = (\beta_T, \beta_I, \beta_F)$ and $C = (\gamma_T, \gamma_I, \gamma_F)$, based on Eq. (3) and Eq. (5) are derived as follows:

(i) Addition of A,B and C

$$(\mathrm{A} \oplus \mathrm{B}) \oplus C = (\alpha_T + \beta_T - \alpha_T\beta_T, \alpha_I\beta_I, \alpha_F\beta_F) \oplus (\gamma_T, \gamma_I, \gamma_F)$$
$$= \{[\alpha_T + \beta_T - \alpha_T\beta_T + \gamma_T] - [\alpha_T + \beta_T - \alpha_T\beta_T]\gamma_T, [\alpha_I\beta_I\gamma_I], [\alpha_F\beta_F\gamma_F]\} \quad (7)$$

$$A \oplus (B \oplus \mathrm{C}) = (\alpha_T, \alpha_I\alpha_F) \oplus (\beta_T + \gamma_T - \beta_T\gamma_T, \beta_I\gamma_I, \beta_F\gamma_F)$$
$$= \{[\alpha_T + \beta_T + \gamma_T - \beta_T\gamma_T] - \alpha_T[\beta_T + \gamma_T - \beta_T\gamma_T], [\alpha_I\beta_I\gamma_I], [\alpha_F\beta_F\gamma_F]\}$$
$$= \{[\alpha_T + \beta_T + \gamma_T - \beta_T\gamma_T - \alpha_T\beta_T - \alpha_T\gamma_T + \alpha_T\beta_T\gamma_T], [\alpha_I\beta_I\gamma_I], [\alpha_F\beta_F\gamma_F]\}$$
$$= \{[\alpha_T + \beta_T - \alpha_T\beta_T + \gamma_T] + [-\alpha_T\gamma_T - \beta_T\gamma_T + \alpha_T\beta_T\gamma_T], [\alpha_I\beta_I\gamma_I], [\alpha_F\beta_F\gamma_F]\}$$
$$= \{[\alpha_T + \beta_T - \alpha_T\beta_T + \gamma_T] - [\alpha_T + \beta_T - \alpha_T\beta_T]\gamma_T, [\alpha_I\beta_I\gamma_I], [\alpha_F\beta_F\gamma_F]\} \quad (8)$$

From Eq. (7) and Eq. (8), it is observed that the addition of NS is associative, $A \oplus B \oplus C = (A \oplus B) \oplus C = A \oplus (B \oplus C)$.

(ii) Scalar Multiplication of $(A \oplus B \oplus C), \lambda \in \mathbb{R}$
Multiplying Eq. (7) with a scalar, λ

$$\lambda(A \oplus B \oplus C)$$
$$= \{1 - (1 - [\alpha_T + \beta_T - \alpha_T\beta_T + \gamma_T] + [\alpha_T + \beta_T - \alpha_T\beta_T]\gamma_T)^\lambda, [\alpha_I\beta_I\gamma_I]^\lambda, [\alpha_F\beta_F\gamma_F]^\lambda\} \quad (9)$$

For data collected from three DMs ($n = 3$), choose $\lambda = \frac{1}{n} = \frac{1}{3}$, then Eq. (9) is simplified as

$$\frac{1}{3}(A \oplus B \oplus C)$$
$$= \left\{1 - (1 - [\alpha_T + \beta_T - \alpha_T\beta_T + \gamma_T] + [\alpha_T + \beta_T - \alpha_T\beta_T]\gamma_T)^{\frac{1}{3}}, [\alpha_I\beta_I\gamma_I]^{\frac{1}{3}}, [\alpha_F\beta_F\gamma_F]^{\frac{1}{3}}\right\}$$
$$= \left\{1 - \sqrt[3]{1 - [\alpha_T + \beta_T - \alpha_T\beta_T + \gamma_T] + [\alpha_T + \beta_T - \alpha_T\beta_T]\gamma_T}, \sqrt[3]{\alpha_I\beta_I\gamma_I}, \sqrt[3]{\alpha_F\beta_F\gamma_F}\right\} \quad (10)$$

Thus, Eq. (10) is the formula for the Arithmetic Mean combined with three SVNN

Zhang *et al.*, [25] also discussed the linguistic variable in NS. Let h_i represents a fuzzy linguistic term. Let $H = \{h_0, h_1, \ldots, h_{2n}\}$ is a set of linguistic terms (LTS). The length of H is 2n+1. For instance, an LTS with five terms is given as below:

$$H = \{h_0 = Extreme\ Low, h_1 = Low, h_2 = Moderate, h_3 = High, h_4 = Extreme\ High\}$$

DM evaluates the influence of the studied factors by assigning a linguistic score, typically $0 - 4$ where $0 = No\ Influence$ and $4 = Very\ High\ Influence$.The linguistic score will be fuzzified based on Table 1.

The linguistic scale of NS, that were discussed by Martina and Deepa [26], was tabulated as the following table.

Table 1
The linguistic variables for Neutrosophic Numbers

Influence Score	Linguistic Variables	Neutrosophic Numbers (T, I, F)
0	No Influence	(0.10,0.90,1.00)
1	Very Low Influence	(0.30,0.70,0.75)
2	Low Influence	(0.50,0.50,0.50)
3	High Influence	(0.80,0.30,0.25)
4	Very High Influence	(1.00,0.10,0.00)

2.1.5 Defuzzification of the aggregated score

After the linguistic score is aggregated using the Arithmetic Mean, the score will be defuzzied, a process of converting a fuzzy output into a single crisp value, using the formula in Eq. (11), as discussed by Deli and Öztürk [27].

Let $S = (T_x(a), I_x(a), F_x(a))$ be a neutrosophic set in universal set U and every element $x \in U$, then the score function of neutrosophic set, denoted by $\sigma_s(a): \mathbb{R} \to [0,1]$, is defined by:

$$\sigma_s(a) = \frac{T_x(a) + I_x(a) - F_x(a) + 1}{3} \tag{11}$$

2.2 Decision-Making Trial and Evaluation Laboratory (DEMATEL)

DEMATEL is a structured methodology used to visualize and analyse complex decision-making problems, particularly when addressing interrelationships between factors. This method is highly effective in identifying cause-effect relationships and prioritizing influential factors within a system. DEMATEL aims to help DM identify and structure complex systems by mapping relationships among factors. It enables a comprehensive view of how factors influence each other and highlights feedback loops within the system.

2.2.1 Algorithm of DEMATEL

DEMATEL is a structured MCDM methodology used to visualize and analyze complex decision-making problems, particularly when addressing interrelationships between factors.

Step 1: Construction of an Initial Direct-Relation Matrix, $\boldsymbol{D}$

Table 2
Initial Direct-Relation Matrix, $\boldsymbol{D}$

Factors	F1	F2	…	F8
F1				
F2				
…				
F8				

Step 2: Normalize the matrix, $\boldsymbol{D}$

The Normalized Initial Direct-Relation Matrix, $\boldsymbol{D_N}$ is calculated using the formula:

$$\boldsymbol{D_N} = \frac{\boldsymbol{D}}{\max(\sum \boldsymbol{D_{row}})} \tag{12}$$

Step 3: Calculation of the Total-Relation Matrix, $\boldsymbol{T}$

The Total-Relation Matrix, $\boldsymbol{T}$, for eight studied factors, is calculated using the formula

$$\boldsymbol{T} = \boldsymbol{D_N} \times (\boldsymbol{I_8} - \boldsymbol{D_N})^{-1}, where\ \boldsymbol{I_8}\ is\ the\ 8 \times 8\ Identity\ Matrix \quad (13)$$

Step 4: Interpretation of the results from the Total-Relation Matrix, $\boldsymbol{T}$

Two key indicators, the significance indicator, s and the relation indicator, r will be calculated using the formula in Eq. (14) and Eq. (15).

$$s_i = Row\ Sum_i + Column\ Sum_i \quad (14)$$

$$r_i = Row\ Sum_i - Column\ Sum_i \quad (15)$$

A positive r value indicates a causal factor, while a negative r suggests an effect. The most positive r values signify the most influential factors, whereas the most negative r values represent factors most influenced by others in the system. This systematic approach provides a clear framework for understanding and addressing complex interrelationships, enabling informed decision-making in various fields.

Step 5: Calculation of the Threshold Total-Relation Matrix, $\boldsymbol{TT}$

The Total-Influence with Threshold Matrix, $\boldsymbol{TT}$ is computed by dividing all the entries in the $\boldsymbol{T}$ matrix with the average of the entries and assign a value of 1 or 0 for the entries that are higher or lower than the average value respectively, where a value of 1 indicating an influence while a value of 0 showing no any form of influence. This $\boldsymbol{TT}$ matrix will be used in RStudio to plot the Network-Relationship Map.

2.3 Case Study: Food Security

Malaysia, while relatively food-secure at the national level, faces rising concerns about sustainability due to rapid urbanization, heavy dependence on food imports and climate-related disruptions. The COVID-19 pandemic further exposed the vulnerability of food supply chains, particularly in highly populated urban areas like Kuala Lumpur and Selangor. Urban households, especially in low-income communities, experienced reduced food access due to rising prices, supply interruptions and unemployment during lockdowns. Limited space and lack of awareness restricted local food production, while over-reliance on imported products raised concerns about long-term FdS. The key factors or criteria relevant to the FdS problem were defined as follows, as discussed by the previous studies [28-34].

Table 3
The eight factors studied in this study

No	Factors	Description
F1	Climate Patterns	How changing weather patterns impact crop yield water availability, and agricultural productivity.
F2	Land and Water Resources	Accessibility to fertile land and sustainable water resources, sustainable practices.
F3	Seed and Fertilizer Availability	Access to quality seeds, fertilizers, and agricultural inputs.
F4	Economic Access	Household income, employment, and purchasing power to afford food.
F5	Population Growth	Rising population and urbanization trends affect food demand.
F6	Food Distribution Network	Proximity to food markets and transportation.
F7	Education and Awareness	Knowledge of healthy eating practices, food safety, nutrition education, food preparation knowledge.
F8	Resilience to Shocks and Crises	Investigating how resilient communities are to sudden shocks (pandemics, natural disasters etc) and the effectiveness of food security safety nets, such as emergency food reserves (adaptive strategies)

3. Results

3.1 Data Collection

The data collection was done using Google Forms, where the respondents are the three DMs from different fields, such as Food Staller, Food and Beverages (F&B) and Lecturer in Management and Technology. Each of these DMs evaluated the effectiveness and interrelationship of the eight studied factors using a linear scale, as in Table 1. The evaluation data from DM1, DM2 and DM3 collected are given as follows respectively:

Table 4
The data from DM1

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	0	2	0	0	0	0	3
F2	2	0	0	0	4	0	0	2
F3	3	0	0	0	0	0	0	0
F4	0	0	2	0	0	0	2	0
F5	1	0	0	0	0	0	2	0
F6	0	0	0	2	0	0	0	0
F7	2	0	3	0	0	0	0	1
F8	0	2	3	3	0	0	2	0

Table 5
The data from DM2

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	4	3	4	4	2	2	3
F2	3	0	4	3	4	3	3	4
F3	4	3	0	3	4	4	3	4
F4	3	2	2	0	4	2	3	4
F5	2	2	4	2	0	2	1	3
F6	2	3	4	2	0	0	4	2
F7	4	3	4	3	3	2	0	2
F8	4	2	4	4	4	3	3	0

Table 6
The data from DM3

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	4	4	3	3	4	3	4
F2	4	0	4	2	4	4	4	3
F3	4	4	0	2	3	4	4	3
F4	3	4	4	0	4	4	4	3
F5	4	3	3	4	0	4	3	4
F6	2	4	4	4	4	0	4	3
F7	4	4	4	4	3	3	0	3
F8	4	4	3	4	4	3	3	0

3.2 Fuzzification Process

The data in Table 4 will be fuzzified by using the linguistic variables for the Neutrosophic Number based on the influence score from DM1 as in Table 1. For example, the evaluation on F8's influence on F1, F2 and F3 were fuzzified using SVNN provided by DM1 are as follows:

$$F8\ to\ F1 - 0 : [0.10, 0.90, 1.00]$$
$$F8\ to\ F2 - 2 : [0.50, 0.50, 0.50]$$
$$F8\ to\ F3 - 3 : [0.80, 0.30, 0.25]$$

Hence, by using the VLOOKUP function available in Microsoft Excel, the fuzzified data from DM1 is given as in Table 7.

Table 7
The fuzzified data from DM1

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.80, 0.30, 0.25)
F2	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)
F3	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)
F4	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)
F5	(0.30, 0.70, 0.75)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)
F6	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)
F7	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.30, 0.70, 0.75)
F8	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)

The same process was repeated to the data from DM2 and DM3 as well and given as Table 8 and Table 9 respectively.

Table 8
The fuzzified data from DM2

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.50, 0.50, 0.50)	(0.50, 0.50, 0.50)	(0.80, 0.30, 0.25)
F2	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)
F3	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)

F4	(0.80, 0.30, 0.25)	(0.50, 0.50, 0.50)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.50, 0.50, 0.50)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)
F5	(0.50, 0.50, 0.50)	(0.50, 0.50, 0.50)	(1.00, 0.10, 0.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.30, 0.70, 0.75)	(0.80, 0.30, 0.25)
F6	(0.50, 0.50, 0.50)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.50, 0.50, 0.50)
F7	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(0.50, 0.50, 0.50)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)
F8	(1.00, 0.10, 0.00)	(0.50, 0.50, 0.50)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)

Table 9
The fuzzified data from DM3

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)
F2	(1.00, 0.10, 0.00)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.50, 0.50, 0.50)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)
F3	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.10, 0.90, 1.00)	(0.50, 0.50, 0.50)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)
F4	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)
F5	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)
F6	(0.50, 0.50, 0.50)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.10, 0.90, 1.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)
F7	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)	(0.80, 0.30, 0.25)
F8	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(1.00, 0.10, 0.00)	(1.00, 0.10, 0.00)	(0.80, 0.30, 0.25)	(0.80, 0.30, 0.25)	(0.10, 0.90, 1.00)

3.3 Data Aggregation and Defuzzification Process

The fuzzified data from all the three DMs (Table 7, Table 8 and Table 9) will be aggregated using the Arithmetic Mean combined with SVNN, from Eq. (10), and the mean value will be defuzzied using Eq. (11) to convert back to a single crisp value.

For instance, the fuzzified data for the influence score of F5 to F2, a_{52} from each of the DMs are given as follows:

$$DM1(a_{52}) = \left(T_1(a_{52}), I_1(a_{52}), F_1(a_{52})\right) = (0.10,0.90,1.00)$$
$$DM2(a_{52}) = \left(T_2(a_{52}), I_2(a_{52}), F_2(a_{52})\right) = (0.50,0.50,0.50)$$
$$DM3(a_{52}) = \left(T_3(a_{52}), I_3(a_{52}), F_3(a_{52})\right) = (0.80,0.30,0.25)$$

Therefore, the aggregated value for the influence score, a_{52}, $M(a_{52})$ is calculated using Eq. (10).

$$\begin{aligned} M(a_{52}) &= [T_x(a_{52}), I_x(a_{52}), F_x(a_{52})] \\ &= \left\{ \begin{array}{c} 1 - \sqrt[3]{\begin{array}{c} 1 - [T_1(a_{52}) + T_2(a_{52}) - T_1(a_{52})T_2(a_{52}) + T_3(a_{52})] + \\ [T_1(a_{52}) + T_2(a_{52}) - T_1(a_{52})T_2(a_{52})]T_3(a_{52}) \end{array}}, \\ \sqrt[3]{\alpha_I \beta_I \gamma_I}, \\ \sqrt[3]{\alpha_F \beta_F \gamma_F} \end{array} \right\} \\ &= \left\{ \begin{array}{c} 1 - \sqrt[3]{1 - [0.10 + 0.50 - 0.10(0.50) + 0.80] + [0.10 + 0.50 - 0.10(0.50)](0.80)}, \\ \sqrt[3]{0.90(0.50)(0.30)}, \\ \sqrt[3]{1.00(0.50)(0.25)} \end{array} \right\} \\ &= \{0.5519, 0.5130, 0.500\}\ (4\ d.p.) \end{aligned}$$

The same calculation process was applied to the other's influence score. By implementing function in Microsoft Excel, the following results are obtained.

Table 10
The aggregated of fuzzified data from the three DMs

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	(0.1000, 0.9000, 1.0000)	(1.0000, 0.2080, 0.0000)	(1.0000, 0.2466, 0.0000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.3557, 0.0000)	(0.5519, 0.5130, 0.5000)	(1.0000, 0.2080, 0.0000)
F2	(1.0000, 0.2466, 0.0000)	(0.1000, 0.9000, 1.0000)	(1.0000, 0.2080, 0.0000)	(0.5519, 0.5130, 0.5000)	(1.0000, 0.1000, 0.0000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.2466, 0.0000)
F3	(1.0000, 0.1442, 0.0000)	(1.0000, 0.3000, 0.0000)	(0.1000, 0.9000, 1.0000)	(0.5519, 0.5130, 0.5000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.2080, 0.0000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.3000, 0.0000)
F4	(0.6698, 0.4327, 0.3969)	(1.0000, 0.3557, 0.0000)	(1.0000, 0.2924, 0.0000)	(0.1000, 0.9000, 1.0000)	(1.0000, 0.2080, 0.0000)	(1.0000, 0.3557, 0.0000)	(1.0000, 0.2466, 0.0000)	(1.0000, 0.3000, 0.0000)

F5	(1.0000, 0.3271, 0.0000)	(0.5519, 0.5130, 0.5000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.3557, 0.0000)	(0.1000, 0.9000, 1.0000)	(1.0000, 0.3557, 0.0000)	(0.5879, 0.4718, 0.4543)	(1.0000, 0.3000, 0.0000)
F6	(0.3918, 0.6082, 0.6300)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.2080, 0.0000)	(1.0000, 0.2924, 0.0000)	(1.0000, 0.4327, 0.0000)	(0.1000, 0.9000, 1.0000)	(1.0000, 0.2080, 0.0000)	(0.5519, 0.5130, 0.5000)
F7	(1.0000, 0.1710, 0.0000)	(1.0000, 0.3000, 0.0000)	(1.0000, 0.1442, 0.0000)	(1.0000, 0.3000, 0.0000)	(0.6698, 0.4327, 0.3969)	(0.5519, 0.5130, 0.5000)	(0.1000, 0.9000, 1.0000)	(0.5879, 0.4718, 0.4543)
F8	(1.0000, 0.2080, 0.0000)	(1.0000, 0.2924, 0.0000)	(1.0000, 0.2080, 0.0000)	(1.0000, 0.1442, 0.0000)	(1.0000, 0.2080, 0.0000)	(0.6698, 0.4327, 0.3969)	(0.7286, 0.3557, 0.3150)	(0.1000, 0.9000, 1.0000)

Next, the data in Table 10 will be defuzzied using Eq. (7). For example, using the value of $M(a_{52})$, the defuzzied aggregated influence score for a_{52}, $\sigma_s(a_{52})$ is computed as follows:

$$\begin{aligned}\sigma_s(a_{52}) &= \frac{T_x(a_{52}) + I_x(a_{52}) - F_x(a_{52}) + 1}{3} \\ &= \frac{0.5519 + 0.5130 - 0.5000 + 1}{3} \\ &= 0.5216(4\ d.p.)\end{aligned}$$

Therefore, the following defuzzied aggregated data is obtained by utilizing the formula into Microsoft Excel.

Table 11
The defuzzied aggregated data

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0.3333	0.7360	0.7489	0.7667	0.7667	0.7852	0.5216	0.7360
F2	0.7489	0.3333	0.7360	0.5216	0.7000	0.7667	0.7667	0.7489
F3	0.7147	0.7667	0.3333	0.5216	0.7667	0.7360	0.7667	0.7667
F4	0.5685	0.7852	0.7641	0.3333	0.7360	0.7852	0.7489	0.7667
F5	0.7757	0.5216	0.7667	0.7852	0.3333	0.7852	0.5351	0.7667
F6	0.4567	0.7667	0.7360	0.7641	0.8109	0.3333	0.7360	0.5216
F7	0.7237	0.7667	0.7147	0.7667	0.5685	0.5216	0.3333	0.5351
F8	0.7360	0.7641	0.7360	0.7147	0.7360	0.5685	0.5898	0.3333

Manual calculations were performed using four decimal places, which may lead to minor differences from the Microsoft Excel result due to the use of the full-precision values in the spreadsheet.

3.4 DEMATEL Process

DEMATEL was integrated on the data in Table 11 to analyse the causal relationship between the eight factors studied using Microsoft Excel, by utilizing the algorithm of DEMATEL as discussed in part 2.2.1.

The Initial Direct-Relation Matrix, $\boldsymbol{D}$ is derived from the defuzzied of aggregated values (Table 11), as given in Table 12. All the entries of the $\boldsymbol{D}$ matrix are normalized by dividing the largest summation of rows, that is 5.4880 (4 d.p.), and the outcome of the Normalized Initial Direct-Relation Matrix is presented in Table 13.

Table 12
The Initial-Direct Relation Matrix, $\boldsymbol{D}$

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8	Sum of Rows
F1	0.3333	0.7360	0.7489	0.7667	0.7667	0.7852	0.5216	0.7360	5.3944
F2	0.7489	0.3333	0.7360	0.5216	0.7000	0.7667	0.7667	0.7489	5.3220
F3	0.7147	0.7667	0.3333	0.5216	0.7667	0.7360	0.7667	0.7667	5.3724
F4	0.5685	0.7852	0.7641	0.3333	0.7360	0.7852	0.7489	0.7667	5.4880
F5	0.7757	0.5216	0.7667	0.7852	0.3333	0.7852	0.5351	0.7667	5.2696
F6	0.4567	0.7667	0.7360	0.7641	0.8109	0.3333	0.7360	0.5216	5.1253
F7	0.7237	0.7667	0.7147	0.7667	0.5685	0.5216	0.3333	0.5351	4.9304
F8	0.7360	0.7641	0.7360	0.7147	0.7360	0.5685	0.5898	0.3333	5.1785

Table 13
The Normalized Matrix, $\boldsymbol{D_N}$

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0.0607	0.1341	0.1365	0.1397	0.1397	0.1431	0.0950	0.1341
F2	0.1365	0.0607	0.1341	0.0950	0.1276	0.1397	0.1397	0.1365
F3	0.1302	0.1397	0.0607	0.0950	0.1397	0.1341	0.1397	0.1397
F4	0.1036	0.1431	0.1392	0.0607	0.1341	0.1431	0.1365	0.1397
F5	0.1413	0.0950	0.1397	0.1431	0.0607	0.1431	0.0975	0.1397
F6	0.0832	0.1397	0.1341	0.1392	0.1478	0.0607	0.1341	0.0950
F7	0.1319	0.1397	0.1302	0.1397	0.1036	0.0950	0.0607	0.0975
F8	0.1341	0.1392	0.1341	0.1302	0.1341	0.1036	0.1075	0.0607

By using the Eq. (9), the Total-Influence Matrix, $\boldsymbol{T}$, can be acquired as follows:

$$\boldsymbol{T} = \boldsymbol{D_N} \times (\boldsymbol{I_8} - \boldsymbol{D_N})^{-1}$$

Table 14
The Total-Influence Matrix, $\boldsymbol{T}$

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	2.8202	3.0783	3.1333	2.9430	3.0804	3.0165	2.8264	2.9532
F2	2.8464	2.9619	3.0816	2.8583	3.0204	2.9645	2.8204	2.9075
F3	2.8655	3.0604	3.0395	2.8827	3.0565	2.9848	2.8441	2.9352
F4	2.8986	3.1253	3.1749	2.9065	3.1131	3.0527	2.8995	2.9941
F5	2.8344	2.9805	3.0708	2.8858	2.9433	2.9534	2.7685	2.8964
F6	2.7089	2.9382	2.9838	2.8045	2.9414	2.7983	2.7280	2.7796
F7	2.6642	2.8452	2.8846	2.7148	2.8088	2.7407	2.5719	2.6925
F8	2.7868	2.9723	3.0188	2.8292	2.9645	2.8738	2.7346	2.7798

The structural correlation analysis was performed by computing the two key indicators, the significance factor, s_i and the relation indicator, r_i using the Eq. (10) and Eq. (11) respectively and the results for the degree of prominence of the eight factors are tabulated as follows:

Table 15
The degree of prominence of the eight factors

Factors	r_i	c_i	$r_i + c_i$	$r_i - c_i$
F1	23.8514	22.4249	46.2763	1.4264
F2	23.4608	23.9621	47.4230	-0.5013
F3	23.6687	24.3872	48.0558	-0.7185
F4	24.1646	22.8248	46.9894	1.3398
F5	23.3330	23.9283	47.2614	-0.5953
F6	22.6826	23.3846	46.0673	-0.7020
F7	21.9227	22.1934	44.1160	-0.2707
F8	22.9598	22.9382	45.8980	0.0216

Based on the $r_i - c_i$ value in Table 15, we can classify the factors in terms of the causal relationship with the respective ranking, as in Table 16.

Table 16
The causal relationship of the eight factors studied

Factors	Descriptions	Causal Relationship	Causer Ranking	Receiver Ranking
F1	Climate Patterns	Net Causer	1	
F2	Land and Water Resources	Net Receiver		4
F3	Seed and Fertilizer Availability	Net Receiver		1
F4	Economics Access	Net Causer	2	
F5	Population Growth	Net Receiver		3
F6	Food Distribution Network	Net Receiver		2
F7	Education and Awareness	Net Receiver		5
F8	Resilience to Shocks and Crises	Net Causer	3	

Next, the Total-Influence with Threshold Matrix, $\boldsymbol{TT}$ can be computed by dividing all the entries in $\boldsymbol{T}$ matrix with the average of the entries and assign a value of 1 or 0 for the entries that are higher or lower than the average value respectively. From the $\boldsymbol{T}$ matrix from Table 14, the average of the entries is 2.9069 (4 d.p.). Thus, the $\boldsymbol{TT}$ matrix is given as follows:

Table 17
The Total-Influence with Threshold Matrix, $\boldsymbol{TT}$

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	1	1	1	1	1	0	1
F2	0	1	1	0	1	1	0	1
F3	0	1	1	0	1	1	0	1
F4	0	1	1	0	1	1	0	1
F5	0	1	1	0	1	1	0	0
F6	0	1	1	0	1	0	0	0
F7	0	0	0	0	0	0	0	0
F8	0	1	1	0	1	0	0	0

3.5 Comparison with DEMATEL Model

In this section, we will compare the results of causal relationships by using the NS-DEMATEL model and DEMATEL model, that is without using any FS in the calculation.

For DEMATEL model, the evaluation from the three DMs is aggregated by the arithmetic mean, which is finding the average value of the respective evaluation before it is analyzed using DEMATEL. Thus, the Initial Direct Relation Matrix, $\boldsymbol{D}$ is given as Table 18.

Table 18
The $\boldsymbol{D}$ Matrix for DEMATEL Model

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0.0000	2.6667	3.0000	2.3333	2.3333	2.0000	1.6667	3.3333
F2	3.0000	0.0000	2.6667	1.6667	4.0000	2.3333	2.3333	3.0000
F3	3.6667	2.3333	0.0000	1.6667	2.3333	2.6667	2.3333	2.3333
F4	2.0000	2.0000	2.6667	0.0000	2.6667	2.0000	3.0000	2.3333
F5	2.3333	1.6667	2.3333	2.0000	0.0000	2.0000	2.0000	2.3333
F6	1.3333	2.3333	2.6667	2.6667	1.3333	0.0000	2.6667	1.6667
F7	3.3333	2.3333	3.6667	2.3333	2.0000	1.6667	0.0000	2.0000
F8	2.6667	2.6667	3.3333	3.6667	2.6667	2.0000	2.6667	0.0000

Thus, the $\boldsymbol{T}$ matrix and causal relationship are given as Table 19 and Table 20.

Table 19
The $\boldsymbol{T}$ Matrix for DEMATEL Model

Factors /Factors	F1	F2	F3	F4	F5	F6	F7	F8
F1	0.8148	0.8326	1.0123	0.8275	0.8732	0.7542	0.8124	0.9030
F2	1.0053	0.7632	1.0620	0.8516	0.9930	0.8144	0.8897	0.9437
F3	0.9655	0.8134	0.8724	0.7931	0.8627	0.7744	0.8303	0.8564
F4	0.8720	0.7728	0.9612	0.6880	0.8495	0.7235	0.8337	0.8269
F5	0.8006	0.6871	0.8574	0.7080	0.6518	0.6564	0.7179	0.7508
F6	0.7629	0.7152	0.8726	0.7341	0.7194	0.5656	0.7485	0.7232
F7	0.9606	0.8167	1.0361	0.8211	0.8551	0.7382	0.7285	0.8475
F8	1.0250	0.9106	1.1233	0.9588	0.9707	0.8271	0.9348	0.8400

Table 20
The causal relationship for DEMATEL ModelT

Factors	r_i	c_i	$r_i + c_i$	$r_i - c_i$	Causal Relationship	Causer Ranking	Receiver Ranking
F1	6.8300	7.2068	14.0368	-0.3768	Net Receiver		3
F2	7.3228	6.3116	13.6344	1.0112	Net Causer	1	
F3	6.7683	7.7973	14.5656	-1.0290	Net Receiver		1
F4	6.5275	6.3822	12.9097	0.1452	Net Causer	4	
F5	5.8300	6.7754	12.6054	-0.9454	Net Receiver		2
F6	5.8415	5.8538	11.6953	-0.0123	Net Receiver		4
F7	6.8040	6.4958	13.2997	0.3082	Net Causer	3	
F8	7.5903	6.6915	14.2818	0.8988	Net Causer	2	

3.5.1 Discussion on the two models

Combine the net causer rankings from Table 17 and Table 20 as in Table 21.

Table 21
The combined net causer rankings

	Net Causer Rankings	
Factors	NS-DEMATEL	DEMATEL
F1	1	
F2		1
F3		
F4	2	4
F5		
F6		
F7		3
F8	3	2

From Table 21, it is observed that there are differences in the net causer rankings between NS-DEMATEL and DEMATEL. NS-DEMATEL ranked F1 while DEMATEL ranked F2 as the top net causer respectively. This suggests that a fundamental disagreement on which factor is the most influential.

Generally, NS-DEMATEL incorporates nonlinear dynamics relation among the influence score while DEMATEL relies on linear relationships and direct influence matrices. For example, NS-DEMATEL ranked F4 as 2nd (higher importance) whereas DEMATEL ranked F4 as 4th (much lower). This could mean NS-DEMATEL able to captures indirect effects that DEMATEL may misses. For F7, NS-DEMATEL classifies it as a net receiver while DEMATEL ranked F7 as a net causer with a rank of 3rd. This may be due to the influence of F7 might rely on mediating factors (indirect or reciprocal influence) that NS-DEMATEL may discounts or overwritten by the nonlinear relationship. Finally, there is a minor difference between the ranking of F8 by NS-DEMATEL and DEMATEL, which is ranked 3rd and 2nd respectively, where DEMATEL gives it marginally more weight in terms of influencing.

Combine the net receiver rankings from Table 17 and Table 20 as in Table 22.

Table 22
The combined net receiver rankings

	Net Receiver Rankings	
Factors	NS-DEMATEL	DEMATEL
F1		3
F2	4	
F3	1	1
F4		
F5	3	2
F6	2	4
F7	5	
F8		

From Table 22, it is observed that NS-DEMATEL ranked F1 as net causer, as discussed in previous part, while DEMATEL ranked F1 as the 3rd net receiver. This is probably due to DEMATEL may underestimate F1's influence, while NS-DEMATEL able to capture its broader network effects. Moreover, NS-DEMATEL ranked F2 as 2nd net receiver, but DEMATEL ranked it as a net causer. This shows that DEMATEL may overemphasize F2's direct effects, while NS-DEMATEL takes it as a more dependent on other factors. On the other hand, NS-DEMATEL ranked F7 as 5th net receiver whereas DEMATEL ranked F7 as a net causer. F7 might act as a mediator in DEMATEL but gets absorbed into network dependencies in NS-DEMATEL.

There is a strong agreement on F3 as the 1st or top net receiver in both models. Both methods agree that F3 is the most dependent factors, meaning it is strongly influenced by other factors in the system. There is a slight difference ranking in F5 and F6. DEMATEL ranked F5 as 3rd, that is less dependent than DEMATEL which ranked F5 as 2nd. NS-DEMATEL (2nd) ranked F6 higher than DEMATEL (4th), suggesting it is more sensitive to system influences in the nonlinear model.

A combined summarised comparison results is tabulated in Table 23.

Table 23
The combined summarised comparison results

Method	Net Impact	Importance degree ranking
NS-DEMATEL	Net Causer: F1,F4,F8	$F1 \succ F4 \succ F8$
	Net Receiver: F2,F3,F5,F6,F7	$F3 \succ F6 \succ F5 \succ F2 \succ F7$
DEMATEL	Net Causer: F2,F4,F7,F8	$F2 \succ F8 \succ F7 \succ F4$
	Net Receiver: F1,F3,F5,F6	$F3 \succ F5 \succ F1 \succ F6$

3.6 Causal Diagram

The causal diagram is constructed based on the values of $r_i + c_i$ as the horizontal axis while the values of $r_i - c_i$, as the vertical axis in the diagram, from Table 14. The causal diagram is plotted using Microsoft Excel, as Figure 1.

The causal diagram is divided into two groups, where the upper half, that the value of the respective $r_i - c_i$ is positive represents the net causer, indicating by the blue dots while the lower part, that the value of the respective $r_i - c_i$ is negative are classified as the net receivers, which indicated by the red dots in Figure 1.

The net causers identified in this study include Climate Patterns (F1), Economic Access (F4) and Resilience to Shocks and Crises (F8) indicating that these factors exert a greater influence on the system than they are influenced by the other factors. Among them, Climate Patterns (F1) have the most significant causes to FdS, as it has the highest positive $r_i - c_i$ values among the other net causer. This indicates that the change in climate patterns are the key forces to shaping the overall dynamics of FdS. It can be observed that the $r_i - c_i$ value for the other two net causers, namely Economic Access (F4) and Resilience to Shocks and Crises (F8) are having a lower $r_i - c_i$ values compared to that of Climate Patterns (F1) Economic Access (F4), which having the second highest positive $r_i - c_i$value, plays an important role in determining the stability of FdS, though it is less dominant that F1. Meanwhile, Resilience to Shocks and Crises (F8) having a minimal influence on the stability of FdS, as indicated by its lowest $r_i - c_i$ values.

On the other hand, Seed and Fertilizer Availability (F3), Food Distribution Network (F6), Population Growth (F5), Land and Water Resources (F2) and Education and Awareness (F7) are categorized as net receivers in this study, which shows that these factors are more affected by other factors than they affect themselves. This means that these five factors are the outcomes of changes in the stability of FdS. Seed and Fertilizer Availability (F3) have the most negative $r_i - c_i$ values, which shows that this is the most affected factor in the system, suggesting that it is significantly affected by the variations of stability of all the five net causers from previous discussions. Likewise, Food Distribution Network (F6), Population Growth (F5), Land and Water Resources (F2) and Education and Awareness (F7) are the sequence of significantly to be affected as the $r_i - c_i$ values are becoming less negative respectively.

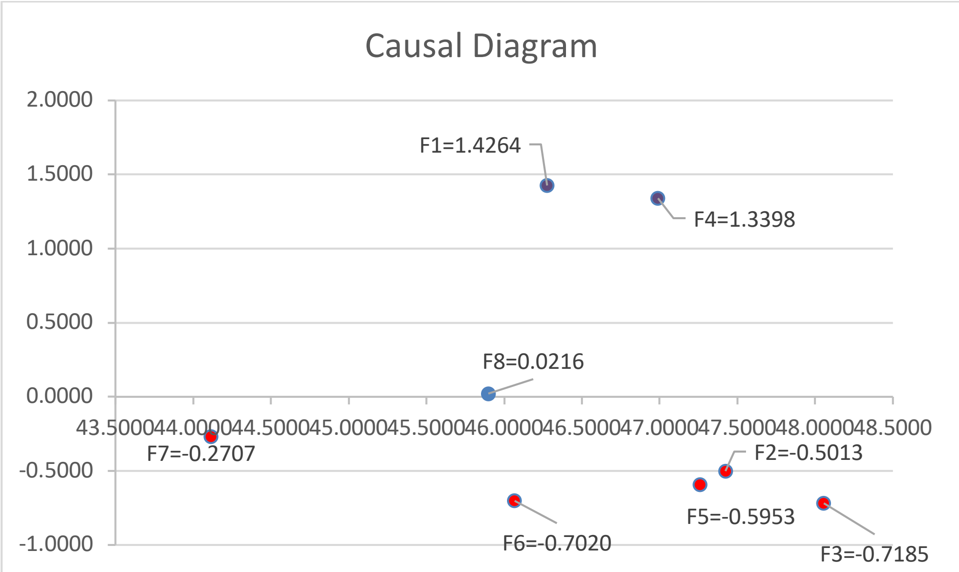

Fig. 1: The causal diagram of eight FdS factors studied

3.7 Network-Relationship Map

The Network-Relationship Map (NRM) is constructed by using the $\boldsymbol{TT}$ matrix, from Table 16 to represent and visualize the relationship among the eight factors studied. By using R codes in RStudio, the Network-Relationship Map is plotted as Figure 2.

From the Figure 2, Climate Patterns (F1) is showing to have a direct influence on Land and Water Resources (F2) $(F1 \rightarrow F2)$. A study conducted by M'Barek *et al.*, 2024 shown that instable climate patterns will reduce the total water yield and affect groundwater recharge. Eventually, the quality of land and water resources will decrease and threaten the stability of FdS [35]. Climate Patterns (F1) also significantly impacting Seed and Fertilizer Availability (F3) $(F1 \rightarrow F3)$, by potentially damaging seed-producing crops, which delay planting seasons and procedure. Climate Patterns (F1) also potentially interrupting fertilizer manufacturing, such as floods forcing fertilizer production and manufacturing process to be delayed. This causes farmers to face repeated climate shocks, which may overuse or mismanage the usage of fertilizer or other methods to compensate for poor yield rate. Furthermore, Figure 2 also indicating that Climate Patterns (F1) having a direct influence on Economic Access (F4) $(F1 \rightarrow F4)$. The findings by a study conducted from Dufrénot *et al*. in 2024 shown that climate patterns such as El Niño, a global climate phenomenon that emerges from variation in winds and sea surface temperatures over the tropical Pacific Ocean, characterized by unusually warmer than average sea surface temperatures in the central and eastern equatorial Pacific, have a minimal inflationary effect, reducing the global economic policy uncertainty. La Niña, a global climate phenomenon characterized by unusually cold ocean temperatures in the Equatorial Pacific, able to raises food inflation, which will eventually amplify the uncertainty in economic [36].

Next, Climate Patterns (F1) has a direct influence on Population Growth (F5) ($F1 \rightarrow F5$). This may probably be due to the short-term shocks, such as famines or critical shortage of food, droughts, and floods. This will lead to increased mortality, as extreme weather can lead to malnutrition and disease outbreak due to famines, which can be seen from a study of 1984 Ethiopian famine from drought by Goddard [37]. Moreover, Climate Patterns also having a direct influence on Food Distribution Network (F6) ($F1 \rightarrow F6$). Instable climate patterns such as extreme rainfall and drought, weakening the food supply chain-related elements such as agricultural output, incomes, prices, food access, food quality and food safety, as what was concluded by a study conducted by Tchonkouang *et al.*, [38]. Additionally, Resilience to Shocks and Crises (F8) can be seen that it is directly influenced by Climate Patterns (F1) ($F1 \rightarrow F8$). Extreme temperatures are due to unpredictable rainfall, which will cause droughts or floods will affect crop yields and disrupt harvesting cycles. The resilience weakened when farmers and food systems were unable to adapt quickly to these changes. For example, a study of impact of the 2022 Pakistan flood disaster had been carried out by Cui *et al.* in 2025 proven that food security was severely affected by the flood [39]. Based on Figure 2, it is observed that neither any arrow is heading towards Climate Patterns (F1), suggesting that this factor is mainly affecting others rather than being influenced.

On the other hand, Land and Water Resources (F2) is having a self-influence ($F2 \rightarrow F2$) as indicated by a self-directed arc in Figure 2. This is because the overuse of land for agriculture leads to loss of soil fertility and reducing future productivity, indicating that this is a negative feedback loop. Also, excessive irrigation leads to the depletion of underground water sources, reducing long-term water availability. Seed and Fertilizer Availability (F3) is affected by Land and Water Resources(F2) ($F2 \rightarrow F3$), in which degraded land required more fertilizers to maintain crop yield rates and directly increase the cost of harvesting. Also, a study conducted by Lin *et al.,* [40] concluded that proper land and water resources management able to increase crop yield and produce higher quality seeds for future planting. Moreover, Land and Water Resources (F2) plays an important role in affecting Population Growth (F5) ($F2 \rightarrow F5$). This is due to positive population growth accelerating land overuse, which worsens the land degradation process. Besides, Land and Water Resources also having a direct influence on Food Distribution Network (F6) ($F2 \rightarrow F6$). Land degradation and irrigation inefficiency will decreases crop yield and production, which leads to supply shortfall and disrupted food distribution. A study conducted from Xie *et al.*, [41] concluded that one should choose suppliers with less water scarcity risks to ensure the stability of food distribution system. Lastly, Land and Water Resources (F2) is directly impacting the Resilience to Shocks and Crises (F8) ($F2 \rightarrow F8$), as shown in Figure 2. This shows that depleted resources cause the communities to become more vulnerable to upcoming unpredictable crises. This can be proven some studies that has been carried out by Kaufmann *et al.*, [42] and Srivastava *et al.*, [43].

From Figure 2, Seed and Fertilizer Availability (F3) is having a direct effect on Land and Water Resources(F2) ($F3 \rightarrow F2$). A study from China conducted by Zhang *et al.*, [44] concluded that different types of fertilizer strategies will varies the soil and water quality. Thus, appropriate fertilizer strategies should be implemented to ensure the good quality of land and water resources and increase crop yield. Besides, Seed and Fertilizer Availability (F3) having a self-influence ($F3 \rightarrow F3$) through feedback loop. This is because a higher quality seed will increase the crop yields, which helps the farmer to generate more income to utilize a fertilizer with a better quality. The seed able to have a better performance and produce even more higher quality crop with the adequate fertilizer. When either input is lacking, the balance of this system is affected. Next, Seed and Fertilizer Availability is having a direct impact on Population Growth (F5) ($F3 \rightarrow F5$) as shown in Figure 2. Improved seed and fertilizers able to boost up the food production and reducing the famine risks. Higher crop yield improves nutrition availability, which help in reducing malnutrition and mortality in a community, as what was conducted and concluded by Headey and Hoddinott [45]. Moreover, Seed and Fertilizer Availability (F3) also having a direct influence on Food Distribution Network (F6) $(F3 \rightarrow F6)$ as shown in Figure 2. Higher quality crop able to be produced by using high quality seed and fertilizer. This leads to the crops able to be last longer and secured during the distribution process, which indeed able to broaden the food distribution network before the crop was degraded, as concluded by a study from Morão [46]. Lastly, Figure 2 also shown that Resilience to Shocks to Crises (F8) is directly affected by Seed and Fertilizer Resources (F3) $(F3 \rightarrow F8)$. The availability of improved seeds and fertilizers enhances agricultural resilience to climate shocks, economics crises and food insecurity by boosting food productivity and stabilizing incomes.

On top of that, Economic Access (F4) has a significant influence on Land and Water Resources (F2) $(F4 \rightarrow F2)$ based on Figure 2. Economic activities such as intensive agriculture, deforestation, and urbanization can lead to soil erosion, desertification and degrading land and water resources, as concluded by a study from Abdelgalil and Cohen [47]. Economic Access (F4) also plays an important role in affecting Seed and Fertilizer Availability (F3) $(F4 \rightarrow F3)$. This is because farmers with limited economic resources frequently face constraints in affording essential agricultural inputs, resulting in reduced crop yields and compromised FdS. Next, Population Growth (F5) is directly affected by Economic Access (F4) $(F4 \rightarrow F5)$ as shown in Figure 2. A study conducted by Glaeser [48] had shown that urbanization increases daily living costs and eventually lead to a higher degree of poverty, discouraging large families and reduce population growth. Moreover, Economic Access (F4) is having a direct impact on Food Distribution Network (F6) $(F4 \rightarrow F6)$. Food distribution system will be secured with sufficient economic support to ensure stable food supply chains as this involved many manpower and transportation system. This is supported by a study conducted by Focker and Fels-Klerx [49]. Lastly, Figure 2 also shown that Economic Access (F4) having a direct influence on Resilience to Shocks and Crises (F8) $(F4 \rightarrow F8)$. Good Economic Access able to help the community to recover faster from any form of shocks, crises or other unpredictable scenarios, as concluded by a study from Eichengreen *et al.*, [50]. This can minimize the loss in food production and optimize the food supply chain during shocks and crises such as natural disaster or outbreak of pandemic.

In addition, Population Growth (F5) is having a direct impact on Land and Water Resources (F2) $(F5 \rightarrow F2)$ based on Figure 2. Tal [51] had carried out a study in 2025 and concluded that the deforestation and urbanization activities will increase along with the population growth. This will then eventually disrupt the land and water resources and leave a negative impact to FdS. Also, Figure 2 shown that Population Growth (F5) have directly influence to Seed and Fertilizer Availability (F3), $(F5 \rightarrow F3)$. Growing population encourage greater use of hybrid seeds and fertilizers to improve yields. A study that was conducted by Speilman and Smale [52] showed that population growth overwhelmed the resources distribution network, causing localized shortages of quality seeds and fertilizers. Next, Population Growth (F5) also having self-influence, indicated by a self-directed loop in Figure 2 $(F5 \rightarrow F5)$. This may probably be due to rising in population will increase the demand and competition for food and resources to sustain daily living. Without proper management, the resources will eventually be depleted, forcing migration to place rich in resources. Finally, based on Figure 2, Food Distribution Network (F6) is directly influenced by Population Growth (F5) $(F5 \rightarrow F6)$. A larger population requires more food and resources, thereby increasing pressure on supply chain and food distribution system, as concluded from a study conducted by Schneider *et al.*, [53].

On the other hand, Food Distribution Network (F6) is having a direct impact on Land and Water Resources (F2) $(F6 \rightarrow F2)$. The development of a food supply chain often relates to deforestation and urbanization to create paths for success food delivery. This indeed negatively impacts the land and water resources which may be polluted or depleted due to construction process, as concluded by a study conducted by Posy *et al.*, [54]. Figure 2 also shown Food Distribution Network (F6) have directly influence to Seed and Fertilizer Availability (F3 $(F6 \rightarrow F3)$. A well-functioning food distribution network ensures seeds and fertilizers reach farmers on time, improving availability and affordability. This can be seen from a study conducted by Boussouf *et al.,* [55], where they successfully demonstrated real-world logistics planning and its influence on the distribution network. Lastly, Food Distribution Network (F6) is also having a direct influence on Population Growth (F5) $(F6 \rightarrow F5)$. Silvestrini *et al.*, [56] had carried out a study in 2023 and successfully proven that stable food supply chain able to improve the population nutritional status of a community.

In contrast, Figure 2 shown that Education and Awareness (F7) is neither having a direct influence on other studied factors nor it is being influenced as there is not any arrow or loop connected to F7. Some findings by other studies had provide evidence that contradict to this result. A study from Hoekstra *et al.,* [57] had concluded that communities with higher education levels are more likely to implement climate (Climate Change, F1) and ecofriendly agricultural practices, such as agroforestry, agriculture and forestry studies and conservation tillage, a method that emphasizes the preservation of soil structure and health, which able to reduce environmental damage. Additionally, proper education enhances the availability and efficient use of seeds and fertilizers (Seed and Fertilizer Availability, F3) by equipping farmers with essential knowledge and practical skills and techniques. This effective utilization of agricultural input contributes to increased crop yields and more sustainable farming systems, as concluded by a study conducted by Pan and Zhang [58]. On top of that, a study from Kim in 2016 concluded that there exists a negative correlation between women's education level and total fertility rate. Women with higher education level tends to practice family planning and effective contraception, which limiting the population growth (Population Growth, F5) [59]. Finally, Wang [60] had conducted a study in 2024 and found out that disaster-preparedness education helps the communities to prepare and foster proper and effective strategies to reduce vulnerability and ensure the continuity of survival during critical events (Resilience to Shocks and Crises, F8) such as natural disasters, pandemic and economic disruptions. For example, emergency food preservation techniques are essential to ensure a stable food supply during food insecurity period. This suggest that more data or other analysis method are needed to provide a result that shows the influence and effect of Education and Awareness (F7) that corresponds to other research.

Last but not least, from Figure 2, Resilience to Shocks and Crises (F8) is having a considerable impact on Land and Water Resources (F2) $(F8 \rightarrow F2)$ as indicated in Figure 2. This is because resilient communities manage land and water resources in a more sustainably way by applying adaptive practices and reducing resources depletion. This can ensure long-term resource availability and agricultural sustainability, which is corresponds to a study carried out by Robinson [61]. Furthermore, Seed and Fertilizer Availability (F3) can be seen to be significantly affected by Resilience to Shocks and Crises (F8) $(F8 \rightarrow F3)$. Resilient communities often establish seed banks that store diverse, locally adapted and climate-resilient seed varieties, which able to ensure a stable supply of planting materials even when commercial channels are disrupted by unexpected crises. There exists a study highlighting the importance of seed banks that conducted by Vernooy *et al.*, [62].Besides, Figure 2 also shown that Resilience to Shocks and Crises(F8) has directly affected the Population Growth (F5) $(F8 \rightarrow F5)$. A study conducted by Suweis *et al.*, [63] evaluated food security by relating population growth to the food availability. The study showed that different population growth rate required different of food availability and resources in the long run.

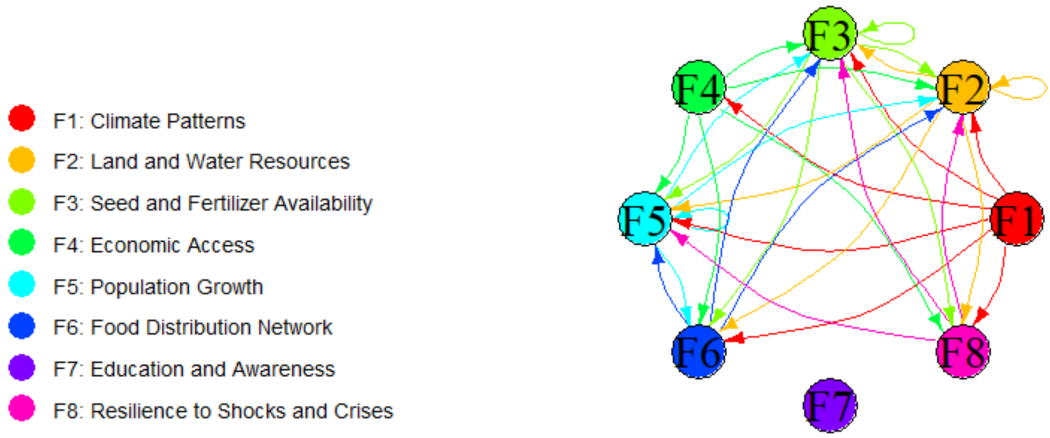

Fig. 2: The network relationship map

4. Conclusions

This research makes a significant contribution by offering an analytical framework that integrates NS and the DEMATEL method to systematically evaluate the interrelationships among FdS factors. The innovative handling of linguistic uncertainty in DMs judgements enhances the reliability of the analysis. The study's identification of Climate Patterns (F1) as the principal net causer and Seed and Fertilizer Availability (F3) as the main net receiver able to provide a direction for policy interventions. By presenting the causal diagram and NRM, the study provides a comprehensive tool to governments, communities and Non-Governmental Organization (NGO) to plan adaptive and sustainable FdS system capable of withstanding future crises.

The limitations of this study include limited DM participations and subjective assessment as there are only involved three DMs' evaluation. The fixed factor set, and exclusion of emerging variables and computational constraints of Microsoft Excel may also affect the generality of the outcomes of this study. Additionally, the unmodeled Non-Linear Interactions is potentially presented in the data.

Therefore, future research is recommended to expand and diversify DM panel to collect different evaluation from different perspective. The factor set should be broadened and incorporate contextual variables to include other factors that are to be discovered. The automated computational implementation of Python or R is a significant boost for the calculation process. Finally, the integration of Non-Linear Modelling Technique should be implemented to reveal any form of non-linear interaction among the studied factors.

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