A Linguistic MCDM Methodology to Investigate Enablers for Food Security in Sustainable Agri-Food Chains

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Abstract

Agriculture has always been the most crucial pioneer for developing countries. Providing clean, healthy, accessible food is becoming a compelling challenge for future farmers. Existing agricultural systems are under threat because of the climate crisis, increasing population, and migration to urban areas. Food security (FS) is one central transformation area to reach sustainable and resilient development. Consequently, in this paper, the main target is to create a comprehensive evaluation environment to detect the most critical enablers of FS in sustainable agri-food chains. The enablers are derived from literature and experts' opinions to create an index for essential facilitators for the FS. A framework based-on fuzzy linguistic measures is presented. The 2-Tuple linguistic (2-TL) model is chosen to be used with multi-criteria decision-making (MCDM) tools. The 2-TL model is a linguistic-based analytical approach that can eliminate information loss during translation. Finally, a real case study is presented to determine the applicability of the suggested methodology and show the managerial implications.

Keywords
2-Tuple linguistic model, Agri-Food Chains, DEMATEL, Food Security, MCDM, Resilience, Sustainable Development

1. Introduction
Agriculture has always been the most critical pioneer for developing countries. Providing clean, healthy, accessible food is becoming a compelling challenge for future farmers. Industrialization helped produce more food with less effort, yet the food transportation from rural areas to city centers and novel production facilities revealed another question about carbon gas emissions.

Nowadays, the changing climate due to carbon gas emissions is affecting every country, and it is called a "climate crisis to attract attention and act immediately by creating public awareness. Yet, public awareness itself is not sufficient to create climate-resilient systems. For this purpose, a more comprehensive and holistic approach is needed. The government, farmers (industry), academicians, and the public should act collectively to obtain sustainable and resilient agri-food chains. Generating sustainable strategies and holistic actions is a powerful way to obtain more durable systems.

As aforementioned, the existing agricultural systems are under threat because of the climate crisis, increasing population, and migration to urban areas. The problem is also addressed in United Nations' Sustainable Development Goals (SDGs) under "Zero Hunger (SDG2)","Responsible Consumption and Production (SDG12)", and "Climate Action (SDG13)" (McElwee et al. 2020). According to the Food and Agriculture Organization of United Nations (FAO), *"Food security (FS) exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy* *life"(FAO, IFAD, UNICEF, WFP and WHO 2021)*. Hence, the FS subject is one major transformation area to reach sustainable and resilient development (FAO 2014).

The FS notion has advanced in the last thirty years to reveal changes in official policy thinking (Berry et al., 2015).The term originated in the mid-1970s when the World Food Conference defined food security in terms of the food supply by guaranteeing basic products' availability and price constancy. Lately, FS's ethical and human rights aspect has been focalized (González-Puetate et al. 2022). Today, we are still talking about food deficit and lack of accessibility. The FS area still needs to be approached from a holistic point of view since the novel technologies from Industry 4.0are seen as a potent facilitator for FS and resilient and sustainable agri-food systems. Integration of technology into existing conventional food systems opens different windows for agricultural production. A novel technology-integrated approach with a collective mindset from all stakeholders of agri-food chainsis seen as a potent solution to obtain FS.

Consequently, in this paper, the main target is to create a comprehensive evaluation environment to detect the most critical enablers of FS in sustainable agri-food chains. The enablers are derived from literature and experts'opinions to create an index for critical facilitators for the FS. A framework based-on fuzzy linguistic measures (Büyüközkan et al., 2021) is presented. The 2-Tuple linguistic (2-TL) model is chosen to be used with multi-criteria decision-making (MCDM) tools. The 2-TL model is a linguistic-based analytical approach that can eliminate information loss during translation (Herrera et al. 2001). While evaluating facilitators that are somewhat abstract and difficult to define, a linguistic-based methodology could be more comprehensible for practitioners and researchers. Plus, it can also create decision-making environments closer to the human cognitive process.

1.1 Objectives

As stated in the literature, FS is an area to be addressed to obtain resilient and sustainable food systems. Creating some knowledge about FS's components and facilitators for constructing a robust,resilient ecosystem is critical. Accordingly, this paper's main objectives are as follows:

- Creating an index for FS,
- Creating enabler evaluation methodology based-on linguistic assessments,
- Creating a flexible and comfortable environment for decision-makers (DMs) to generate related actions and strategies to increase FS.

This paper proposed a 2-TL-DEMATEL (Quader et al. 2016) methodology for enabler assessment for FS by considering these objectives. The remainder of this paper is organized as follows: Section 2 gives the theoretical background with a literature review. Section 3 presents the methodological background with 2-TL-DEMATEL methodology details. Section 4 provided the case study to test the plausibility of the suggested methodology. Section 5 gives the results and discussion, and finally, Section 6 provides the conclusions.

2. Literature Review

This section will explain the theoretical background of FS and its importance in agri-food chains.

2.1 FS and Sustainable Agri-Food Chain

When the recent literature about FS and sustainable agri-food systems is examined from the academic literature, network visualization in Figure 1 is obtained according to the keyword occurrences by VosViewer[1] software. This map summarizes the most critical notions mentioned in the academic literature. This map also shows the highlighted features, benefits, and technologies in the FS and sustainable agri-food area.

Four groups are obtained in the map. The first group, the yellow one, covers the area related to transparency and the control of the supply chain. The academic literature emphasizes the use of novel digital technologies such as blockchain in order to augment transparency and obtain food safety (González-Puetate et al. 2022; Oruma et al., 2021; Lin et al. 2018; Adam et al. 2016; McElwee et al. 2020; Joshi et al. 2022).The blue group focuses on the relationship between climate change and the FS and sustainable supply chains. In this group, the risks arising from climate change and its effects on sustainable agri-food chains are emphasized (He et al. 2013; Lipper et al. 2014;

[1]https://www.vosviewer.com

Campbell et al. 2014; Dinesh et al. 2018; Acosta-Alba et al. 2019; Budiman 2019; Mattas et al. 2022; Delian et al. 2019).

The third group, the green one, covers the supply chain management systems with IoT (internet of things) integration and also end-user communication. This group most focuses on the end-user preferences and the supply chain and demand variation due to the COVID-19 pandemic (Alabi et al. 2022; Ebata et al. 2021; Galanakis et al. 2021; Hamid et al. 2021; Joshi et al. 2022; Musa et al. 2021).

The final group, the red one, goes around the intersections between sustainable development, sustainability, and the FS. In this group, the importance of FC is emphasized for sustainable development (Asian et al. 2019; McElwee et al. 2020; Pan et al. 2021; Roy et al. 2018).

In summary, the academic literature accentuates the importance of FS as a major facilitator for agricultural transformation and sustainable development. For that purpose, various models have been proposed: Vulnerability analysis, technology-driven models for food security, risk analysis, etc.(Cruz et al. 2021; Wang et al. 2021; Ali et al. 2020; Yadav et al. 2021). Yet, none of them have approached this as a linguistic MCDM process first to create a better understanding and analysis of the FS subject, then select the major facilitators from industry and academia. This paper aims to fill this gap in the literature and provide a holistic enabler assessment model for the FS (Figure 1).

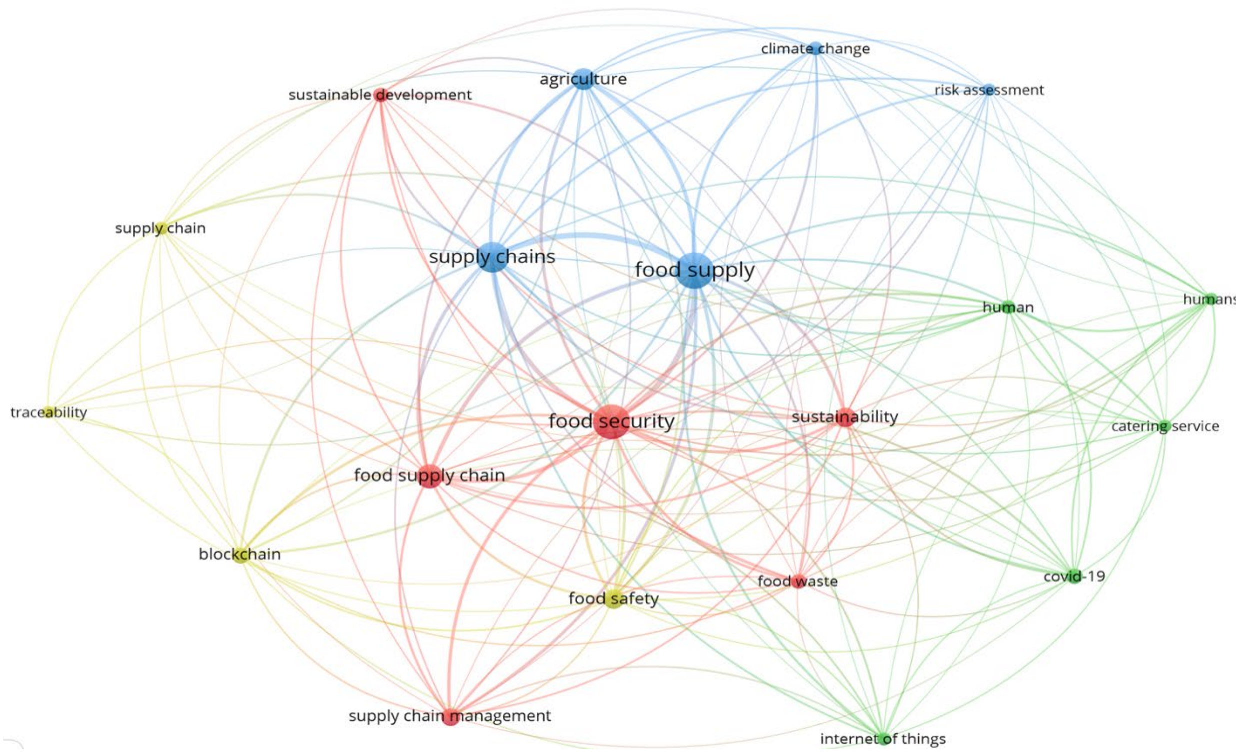

Figure 1. Network map visualization for FS and sustainable agri-food chains.

2.2 Enabler for Food Security in Sustainable Agri-Food Chains

FAO defined FS long ago, yet the definition is still growing with the changing ethical and economic environments. Recently, FAO has determined four main pillars for FS: *Availability, Access, Utilization, and Stability* (FAO, 2014).These four pillars should be addressed simultaneously, and the strategies and actions are needed to be taken according to them.

Actually, four pillars suggest a basis for an agricultural transformation for a more equal and resilient world. Linking these pillars with agricultural transformation dimensions may be a potent and robust solution for sustainable resilience. Consequently, our model aimed to link the agricultural transformation (Boettiger et al. 2017; Berry et al. 2015) with major FS pillars from FAO.

Availability covers the food supply of FS and is mostly related to the food production market.
Access means the food supply sufficiency, which is highly related to the agricultural policies and market prices.
Utilization means the nutritional quality of the produced and supplied food. It is mostly related to agricultural activities, policies, and production conditions.
Stability covers access to food periodically. This is highly related to economic factors, policies, and weather conditions.
In this model, we merged and linked these pillars to the agricultural transformation's key enablers as presented at the end of Figure 1 (Alabi et al. 2022; Yadav et al. 2021; Lipper et al. 2014; Campbell et al. 2014; Berry et al. 2015; Hilaire et al. 2022). Also, the triple bottom line of sustainability is linked to the four main pillars of FS. Therefore, the aim was to create a comprehensive overview of agricultural transformation for sustainable and resilient systems with good FS.

The academic, industrial literature and expert's opinion have been used to generate the suggested model. The details of our model will be given in the Methods Section.

3. Methods

This section will provide the methodological background for the technology assessment framework. This section will give the MCDM methodology and its components as preliminaries. First, in Figure 2, the generated model for FS enablers is presented. Then for the prioritization and investigation, the 2-TL-DEMATEL methodology will be given.

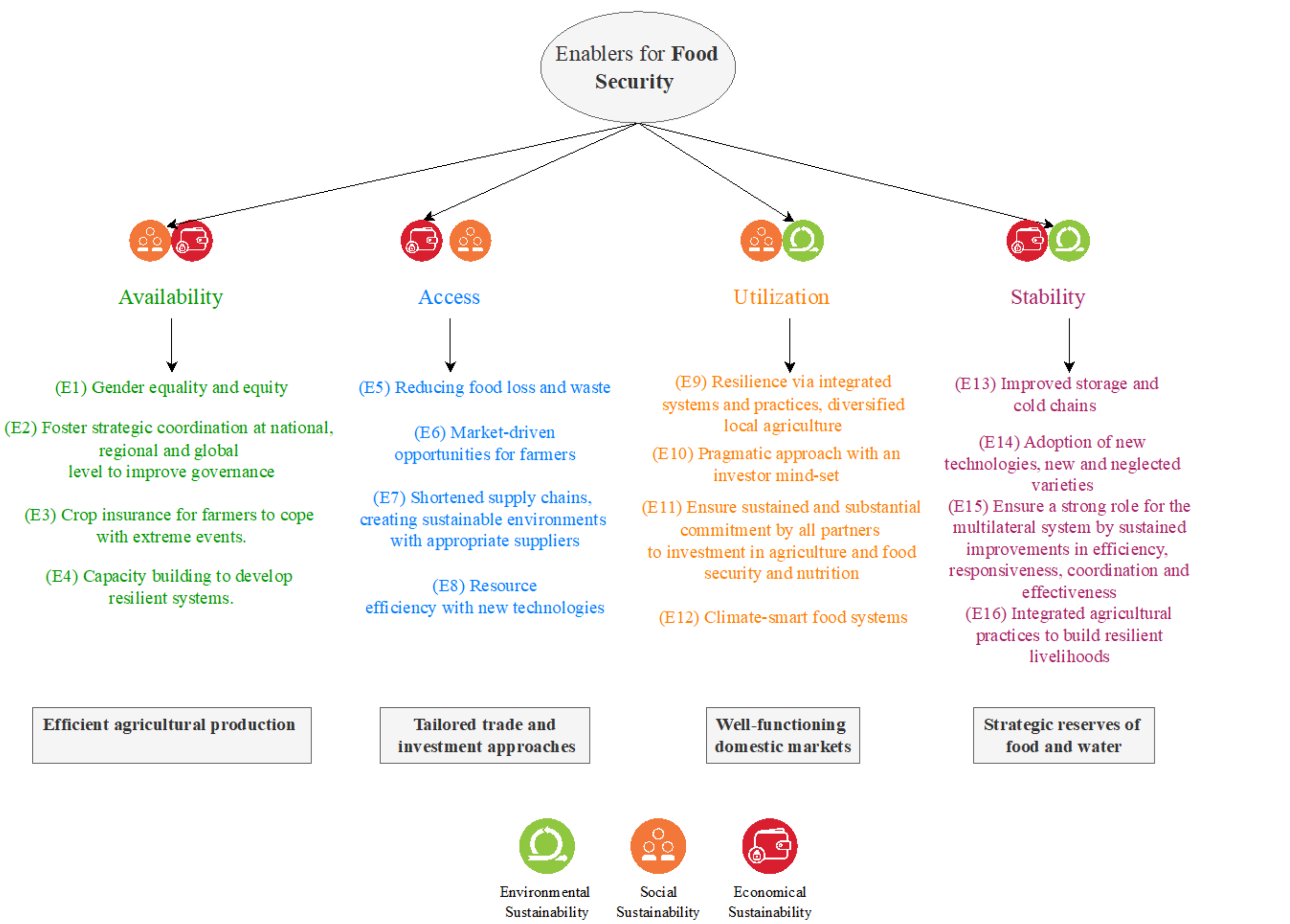

Figure 2. Suggested model for enabler investigation for FS in sustainable agri-food chains (Alabi et al. 2022; Yadav et al. 2021; Lipper et al. 2014; Campbell et al. 2014; Berry et al. 2015; Hilaire et al. 2022).

3.1 2-Tuple Linguistic Model

The 2-Tuple linguistic model is a fuzzy logic-based model (Zadeh, 1965).It reduces information loss while transforming linguistic data into numerical form. The 2-Tuple fuzzy linguistic representation model makes it possible to represent linguistic information with a 2-Tuple form of *(s, α)*, where *'s'* is a linguistic label and *'α'* is a numerical value representing this symbolic translation's value (Herrera et al., 2000). For the necessary and basic definitions, readers can refer to (Martínez et al. 2015). The leading translation equation of 2-TL is given as follows:

$$\Delta_s : [0, g] \rightarrow \bar{S}$$
$$\Delta_s(\beta) = (S_i, \alpha), with \begin{cases} i = round(\beta) \\ \alpha = \beta - i \end{cases} \quad (1)$$
$$S_i \in S \Rightarrow (S_i, 0)$$

A *Linguistic Hierarchy (LH)* is the union of all levels *t,* where each level *t* corresponds to a linguistic term set symmetrically distributed with an odd granularity (Martínez et al. 2015). The transformation function to translate a linguistic term set with granularity *n(t)* to a linguistic term set having granularity *n(t')* is as follows:

$$TF^{t}_{t'} = \left(S_i^{n(t)}, \alpha^{n(t)}\right) = \Delta\left(\frac{\Delta^{-1}(\left(S_i^{n(t)}, \alpha^{n(t)}\right) \times (n(t') - 1)}{n(t) - 1}\right) \quad (2)$$

The transformation function enables multi-granular information to become one linguistic domain.

3.2 DEMATEL

DEMATEL (Gabus et al., 1972) is an accurate MCDM tool that depicts the importance of related criteria. It also makes it possible to determine the causal relationships between evaluation criteria (Büyüközkan et al. 2010) and is suggested for the criteria weighting process. It is utilized in this study's framework because of its ability to check the interdependence among the proposed criteria and extract their interrelationships. Evaluating these relationships can help companies increase the efficiency of their own evaluation processes. Evaluation dimensions are determined according to an extensive literature search and additional interviews with industrial experts.

3.3 Group Decision Making

MCDM aims to discover the most appropriate alternative by conceiving multiple criteria concurrently. Group Decision Making (GDM) may be adequate to reach an objective solution in this procedure. GDM involves various DMs having different backgrounds or points of view and handling the decision process distinctive from others. However, each DM has a shared awareness for cooperating with each other to achieve a collective decision. Particularly while having haziness and uncertainty, reaching consensus for a decision in a group with different opinions turns out to be more critical. Generally, GDM problems are solved using classic approaches, such as the majority rule, minority rule, or total agreement. Yet, these techniques do not assure an acceptable solution for all DMs (Büyüközkan et al. 2015).

In this paper, a consensus-reaching process is followed by the Delphi approach. Delphi is a communication instrument that facilitates group decision-making. The Delphi process is very efficient for supporting a group of individuals to handle complicated problems as a group (Büyüközkan 2004).The method is based on expert knowledge, and the group is principally formed with knowledgeable and expert contributors.

The assessment made by DMs depends on their judgment and is subjective. Accordingly, instead of crisp numbers, the linguistic variables are given to the DMs to represent their data's uncertain and subjective nature.

3.4 2-TL DEMATEL Technique for Enabler Investigation for FS

The DEMATEL technique can convert the interrelations between factors into an intelligible structural model of the system and divide the interrelations into cause-and-effect groups. Hence, it is an appropriate and valuable tool to analyze and rank the interdependent relationships among factors in a complex system for long-term strategic decision-making and indication of improvement scopes. The formulating steps of the 2-TL integrated DEMATEL method can be summarized as follows (Quader et al., 2016):

Step 1. Constructing the average matrix (*A*).
In this step, DMs give their evaluations, (S_{ij}, α_{ij}). They evaluate the direct effect between criteria *i* and *j*.

Step 2. Calculating the initial direct influence matrix (*D*).
In this step, the matrix D is obtained by normalizing the matrix A with the following relation:

$$D = s.A$$
$$s = min\left[\frac{1}{max_{1\le i\le n}\sum_{j=1}^{n}\left|\Delta^{-1}(S_{ij},\alpha_{ij}).\right|}, \frac{1}{max_{1\le j\le n}\sum_{i=1}^{n}\left|\Delta^{-1}(S_{ij},\alpha_{ij}).\right|}\right] \quad (3)$$

Step 3. Calculating the total direct/indirect influence matrix (*T*).
The total direct/indirect influence matrix is defined as the following relation:

$$T = D(I-D)^{-1} \quad (4)$$
$$T = \left[\Delta^{-1}(S_{ij}, t_{ij})\right]\ i,j = 1,2 \ldots n$$

In this relation, *I* is the identity matrix. In the *T* matrix, *d* and *r* values can be derived to determine the direct/indirect relationships between criteria. *d* refers to the dispatcher, and *r* indicates the receiver. These values can be obtained by using the following relation:

$$d = d_{n\times 1} = \left[\sum_{j=1}^{n}\Delta^{-1}(S_{ij}, t_{ij})\right]_{n\times 1}$$
$$r = r_{n\times 1} = \left[\sum_{i=1}^{n}\Delta^{-1}(S_{ij}, t_{ij})\right]_{1\times n} \quad (5)$$

$r_i$gives the summation of the direct and indirect effects of criterion on the others. If c_i is the sum of the *jth* column of the matrix *T*, then it refers to the sum of the direct and indirect effects that the criterion receives from others. In addition, when *j=i,, $(d_i + r_i)$* gives an index of the strength of influences given and received, it refers to the degree of importance of criterion *i* in the problem. Also, if $(d_i\text{-}r_i)<0$, then criterion *i* is being affected by other criteria (Tzeng *et al.*, 2007). Moreover, if $(d_i\text{-}r_i)>0$, it means that the degree of affecting others is stronger than the degree of being affected.

Step 4. Analyzing the cause-and-effect diagrams.
In this step, influence diagrams are obtained to investigate the cause-effect relations between criteria. Comprehensive details of the recommended methodology for BC technology evaluation are presented in Figure 3.

4. Case Study

This section presents the real case study application to assess the enablers for FS in sustainable agri-food chains. The case is first presented to test the applicability of the suggested methodology and then to show the managerial implications based on the suggested linguistic-based MCDM methodology.

For that purpose, at the beginning, the decision-making group containing three experts is formed to obtain the evaluations for the enablers detected as in Figure 2. Each DM (expert) has his/her own experience on the subject; therefore, two different granulated linguistic term sets are provided to them. Table 1 gives the provided linguistic sets.

Table 1. Five and nine scaled linguistic evaluation sets

2-TL linguistic sets	
S^5	*None (N)-Low(L)- Medium (M)- High(H)-Perfect(P)*
S^9	*None (N)-Low (L)-Medium Low (ML)-Almost Medium (AM)- Medium (M)-Almost High (AH)-High(H)- Very High (VH)-Perfect(P)*

Thanks to the 2-TL model five scaled evaluation set is provided to the academician who works on supply chains. Nine scaled evaluation set is suggested to the other two experts who are more experienced on the sustainability and the FS areas. Different sets are provided so that the experts would feel comfortable and avoid uncertainty while evaluating and reaching a more objective conclusion. The detailed steps of the case study are defined followingly:

Step1: Definition of enablers for FS for sustainable agri-food chains and creating a hierarchical decision model.
In this step, as aforementioned in Section 3, four main pillars from FAO are used as major dimensions and according to the literature and experts' opinion four main dimensions and sixteen enablers are defined for FS.

Step 2: Collecting each DM's assessments to obtain enablers' interdependencies and importance. Here, Table 2 is provided for the four main dimensions. The assessment of each DM is provided.
While constructing the average matrix, each DM gave their evaluations, (S_{ij}, α_{ij}). They evaluate the direct effect between criteria *i* and *j*.

Table 2. Evaluations of each DM for main dimensions.

DM1	**0.45**			
	Availability	Access	Utilization	Stability
Availability	0	H	VH	AM
Access	M	0	AH	AH
Utilization	ML	ML	0	L
Stability	AH	H	VH	0
DM2	**0.35**			
	Availability	Access	Utilization	Stability
Availability	0	ML	H	M
Access	M	0	AH	H
Utilization	ML	ML	0	L
Stability	AH	VH	P	0
DM3	**0.25**			
	Availability	Access	Utilization	Stability
Availability	0	L	H	M
Access	M	0	M	H
Utilization	L	L	0	L
Stability	H	P	P	0

Step 3: First normalization of DMs' assessments under the linguistic set containing higher granularity (S^9).
This stage is for normalizing the different granulated data. According to their experience, the decision-making group used two different granulated sets. Hence, to obtain unified assessments, normalization is necessary. Thanks to the *LH* approach of the 2-TL model, the evaluations are normalized by using Eq. (2).

Step 4: Construct the average matrix (A).
The average matrix is obtained by aggregating the unified assessments of each DM. The aggregation is obtained by applying the *Weighted Average Operator* (Martínez et al. 2015) of the 2-TL model. Table 3 is provided for the aggregated average matrix (A).

Table 3. Aggregated average matrix for dimensions of 2-TL DEMATEL

	Availability	Access	Utilization	Stability
Availability	0.00	(L, 0.30)	(ML,0.25)	(L,0.25)
Access	(L,0.40)	0.00	(ML, -0.33)	(ML, -0.05)
Utilization	(L, -0.30)	(L, -0.30)	0.00	(L,0.43)
Stability	(ML, -0.17)	(ML,0.38)	(AM,0.35)	0.00

The same stages can also be applied to the sub-criteria (enablers). The same steps can be followed to obtain their weights and interrelationships.

*Step 5:*Calculate the initial direct influence matrix (D).

*Step 6:*Calculate the total direct/indirect influence matrix (T).

Step 7: Analyzing the cause-and-effect diagrams and prioritization of dimensions and enablers.

Steps 5, 6 and 7 contain the normalization of *matrix A*, obtaining the interrelations of enablers and dimensions. The details of the results will be provided in the following section.

5. Results and Discussion

After applying the 2-TL-DEMATEL steps, the prioritization of dimensions and enablers and the interrelation of dimensions and enablers are obtained. Here Figure 3 shows the importance of dimensions. The same process is applied to enablers as well.

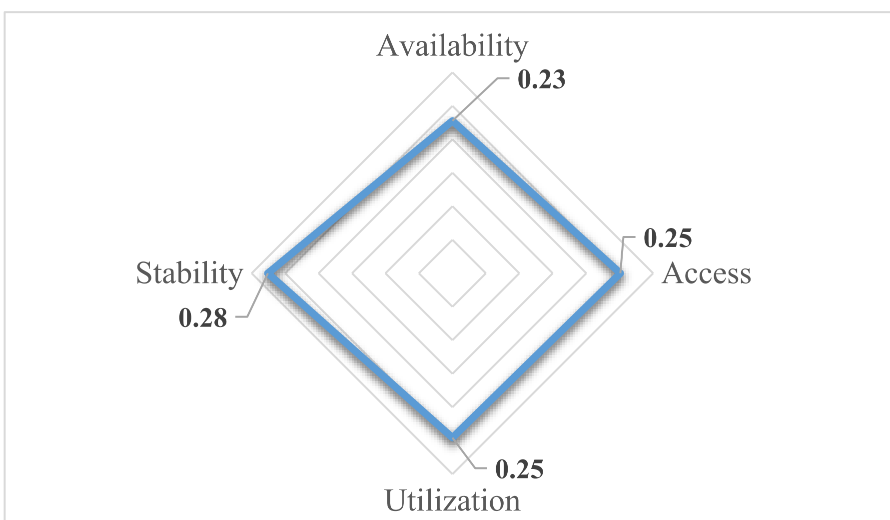

Figure 3. Dimension importance obtained from 2-TL-DEMATEL

The following table also gives the overall importance of enablers and dimensions together. Also, on the following page, Figure 4 shows the *d+r* and *d-r* values to investigate the cause-effect relations between dimensions and enablers (Figure 4).

If $(d_i-r_i)>0$, it means that the degree of affecting others is more substantial than the degree of being affected. Utilization covers the "nutrition quality" of the produced food. Accordingly, for the dimensions, even the stability is obtained as the most critical dimension for FS, with the positive *d-r value, Utilization* dimension is the effecting all the other dimensions. Hence, following the strategies for increasing nutrition quality will facilitate the possibility of addressing the other three dimensions.

When the overall ranking is investigated (Table 4), under the *Stability* dimension, the *"Integrated agricultural practices to build resilient livelihoods (E16)"*enabler is obtained as the most critical one. This enabler also has a causal property, which means it can affect other enablers under the *Stability* dimension. To create a roadmap for agricultural transformation and FS, E16 may be a potent solution to reach more sustainable and resilient systems.
The second important enabler, *"Climate-smart food systems (E12),"* is under the *Utilization* dimension. Yet, it has an effect property with a negative *d-r value.* Therefore, in order to create a strategy based on the *Utilization* dimension, E10 and E11 can be a potent way to start creating strategies and actions because they both have causal properties under the *Utilization* dimension.

Table 4. The overall importance of enablers and their causal relations

Main Pillars	**Imp.**	**Enablers**	**Imp.**	**Cause/Effect**	**Overall Weights**	**Rank**
Availability	0.23	Gender equality and equity	0.23	**Effect**	0.052	14
		Foster strategic coordination at the national, regional, and global levels to improve governance	0.25	**Cause**	0.057	13
		Crop insurance for farmers to cope with extreme events.	0.25	**Effect**	0.057	12
		Capacity building to develop resilient systems.	0.28	**Cause**	0.064	9
Access	0.25	Reducing food loss and waste	0.25	**Effect**	0.062	11
		Market-driven opportunities for farmers	0.20	**Effect**	0.049	15
		Shortened supply chains, creating sustainable environments with appropriate suppliers	0.26	**Cause**	0.065	7
		Resource efficiency with new technologies	0.30	**Cause**	0.074	3
Utilization	0.25	Resilience via integrated systems and practices, diversified local agriculture	0.26	**Effect**	0.065	8
		Pragmatic approach with an investor mindset	0.16	**Cause**	0.041	16
		Ensure sustained and substantial commitment by all partners to investment in agriculture and food security and nutrition	0.28	**Cause**	0.070	5
		Climate-smart food systems	0.30	**Effect**	0.074	2
Stability	0.28	Improved storage and cold chains	0.22	**Effect**	0.063	10
		Adoption of new technologies, new and neglected varieties	0.25	**Cause**	0.071	4
		Ensure a strong role for the multilateral system by sustained improvements in efficiency, responsiveness, coordination, and effectiveness	0.24	**Effect**	0.066	6

		Integrated agricultural practices to build resilient livelihoods	0.29	**Cause**	0.081	1

Figure 4. *d+r* and *d-r* values for dimensions and enablers

6. Conclusion

This paper aims to create a linguistic information based MCDM model for enabler investigation for FS in sustainable agri-food chains. As aforementioned, FS is seen as an essential notion to create resilient agricultural systems. Agriculture is one of the fields where the need for secure and traceable products is rising; therefore, this paper targeted the agriculture sector for FS.

Since FS is linked to the agricultural transformation, the paper aims to create a holistic approach for both FS and transformation by linking them together. This paper generated main dimensions and sixteen different enablers for FS and agricultural transformation. The same methodology also allows us to see the cause-and-effect relations between these dimensions; thus, this framework guides practitioners to precisely understand FS and its importance for resilient agri-food systems. Moreover, the same framework may also guide the policymakers or DMs in the organizations to select the most suitable strategy according to the prioritization of these enablers.

In this paper, three different DMs are used during the case study. The number of DMs could be a limitation for this paper, yet according to the literature, the number is enough to reach an objective solution (Büyüközkan et al. 2021). Yet, for future studies, the number of DMs could be increased. Moreover, the same 2-TL-DEMATEL methodology could be applied to choose the right strategy and actions according to the enabler prioritization.

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