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Enhancing Sustainability through Collaboration: A *2TL-DAD* Assessment Framework for Sustainable Agri-Food Models

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Abstract

Collaboration is increasingly recognized as a key enabler of sustainability in complex agri-food systems. This study proposes a novel decision-support framework—2TL-DAD (2-Tuple Linguistic DEMATEL–Axiomatic Design)—to assess which sustainable agriculture models best foster meaningful stakeholder collaboration. The method integrates expert-based linguistic evaluations, causal relationship mapping, and design-performance alignment to provide structured, context-sensitive prioritization. A case study with Turkish experts was conducted to test the model's applicability and robustness under varying stakeholder priorities. Results reveal that Agroecology and Permaculture consistently outperform other alternatives. The framework offers a flexible tool for supporting policy and strategy design in sustainability transitions, with future potential for adaptation across different decision contexts and criteria.

Keywords
Sustainable agriculture models, collaboration, 2-Tuple Linguistic Model, DEMATEL, Axiomatic Design.

1. Introduction
The existing industrial agri-food system is commonly acknowledged as environmentally unsustainable, socially unequal, and economically inequitable (Govaerts et al., 2021). Predominantly reliant on monoculture, high chemical inputs, intensive resource utilization, and globalized supply chains, this system contributes to severe environmental issues, including soil degradation, loss of biodiversity, water pollution, and elevated greenhouse gas emissions. Economically, it consolidates power within multinational agribusinesses, sidelining smallholder farmers and intensifying global food production inequalities. Additionally, it perpetuates social injustices such as land dispossession, poor labor conditions, and the erosion of local traditions and cultural knowledge.

Advances associated with Industry 4.0 have created opportunities to transform agri-food systems, enhancing both efficiency and sustainability. Technologies such as the Internet of Things (IoT), blockchain, big data analytics, and precision agriculture have modernized conventional agricultural practices, fostering transparency and enabling informed, data-driven decisions. For instance, blockchain has notably improved traceability, sustainability, and supply chain effectiveness (Mohapatra et al., 2023).

The integration of these technologies has significantly enhanced stakeholder interactions within agri-food systems, enabling collaborative environments that allow farmers, distributors, and consumers to actively engage, exchange information, and participate in joint decision-making (Dania et al., 2018). Thus, meaningful stakeholder collaboration becomes pivotal to effectively tackle complex sustainability challenges, improve resource management, mitigate conflicts, and achieve balanced sustainable development outcomes. Such collaboration especially empowers smallholder farmers by increasing their access to resources, markets, and socio-economic opportunities.

Q. F. Zhang, (2024) emphasizes the need for sustainability approaches that integrate ecological goals with socio-political transformation, particularly within the context of power relations, equity, and justice in global food systems. The study calls for further research on how sustainable agriculture models can incorporate emerging technologies without reinforcing existing inequalities. It highlights a gap in understanding how collaboration is shaped by these dynamics. Responding to this call, the present paper focuses on assessing which sustainable agriculture models are most effective in enabling meaningful collaboration among diverse stakeholders. This focus supports both the sustainable and digital transformation of agri-food systems in line with the Sustainable Development Goals (SDGs).

While the importance of collaboration is widely acknowledged, there remains a limited number of studies that systematically examine its enabling factors within the context of sustainable agri-food systems. This gap motivates the core research question of this paper: "*Which sustainable agriculture models facilitates meaningful collaboration most effectively?"*. This paper builds on the foundational work of Dania et al. (2018), which explores collaboration behavior in agri-food supply chains through a structured framework. In parallel, Zhang (2024) provides a critical comparative analysis of sustainable agriculture models, highlighting their distinct approaches to ecological and systemic transformation. Both studies serve as the basis for this research, which aims to methodologically examine the relationship between sustainable agriculture models and stakeholder collaboration through a structured decision-making lens.

This technological evolution has notably increased interactions among system components within agri-food supply chains. Traditionally isolated stakeholders—farmers, processors, distributors, and consumers—now actively engage in collaborative environments where information sharing and collective decision-making become commonplace (Massari et al., 2023). Such collaborative networks empower stakeholders to express their demands and expectations directly, enhancing transparency and accountability within supply chains.

This paper is organized as follows: Following the introduction, Section 2 gives the brief investigation of relevant literature and detected collaboration criteria and sustainable agriculture models. Section 3 describes the methodology, discussing in detail the suggested integrated multi-criteria decision-making (MCDM) methodology integrated with 2-Tuple Linguistic (2TL) Model. Section 4 presents the case study applied with Turkish experts with relevant results and discussions presented in Section 5. Then, Section 6 concludes the paper with suggestions for further research.

2. Literature Review

To systematically map the academic landscape on collaboration within sustainable agri-food systems, a search was conducted in the Web of Science database using the following query: *TS=(collaboration AND ("agri-food system" OR "agricultural supply chain" OR "agri-food supply chain*" OR "agriculture" OR "sustainable agriculture")),* covering the period from 2020 to 2025.

The bibliometric analysis was performed using *Bibliometrix* (Aria & Cuccurullo, 2017), an R-based open-source tool designed for comprehensive science mapping. Bibliometrix applies quantitative techniques such as co-word analysis, thematic mapping, and dimensionality reduction to examine the intellectual and conceptual structure of a research domain.

2.1 Collaboration in Agri-food Systems

Recent research has increasingly highlighted the pivotal role of collaboration in advancing sustainability transitions within agri-food systems. Alonso-Adame et al., (2025) demonstrate that collaboration between farmers and public institutions not only facilitates the scaling of sustainable innovations but also enhances the resilience of farming systems through trust-based networks and coordinated actions. Similarly, Vahdanjoo et al., (2025) emphasize that the digital transformation of agri-food systems critically depends on fostering interdisciplinary collaboration among stakeholders, ensuring the successful adoption of technologies such as blockchain, IoT, and AI. Both studies converge on the importance of building strong, trust-driven, and technologically interconnected networks to overcome systemic barriers in sustainability transitions. These insights underline that collaboration is no longer a peripheral issue but a central mechanism for enabling both technological adaptation and socio-ecological resilience in agri-food supply chains.

Building upon these foundations, this study investigates which sustainable agriculture models most effectively facilitate meaningful collaboration among heterogeneous stakeholders, aiming to support the digital and sustainable transformation of agri-food systems in line with the Sustainable Development Goals (SDGs). The bibliometric analyses provide strong evidence of the evolving research landscape in sustainable agri-food systems. The word frequency over time graph (Figure 1) indicates a steady increase in the academic focus on key sustainability-related terms between 2021 and 2025. Particularly, while traditional topics such as “agriculture,” “sustainability,” and “climate change” maintain dominant trajectories, “collaboration” has shown a consistent and notable rise, especially after 2023 (Murphy et al., 2023; Vahdanjoo et al., 2025). This trend reflects an emerging recognition of the critical role collaboration plays in addressing complex sustainability challenges within agri-food supply chains

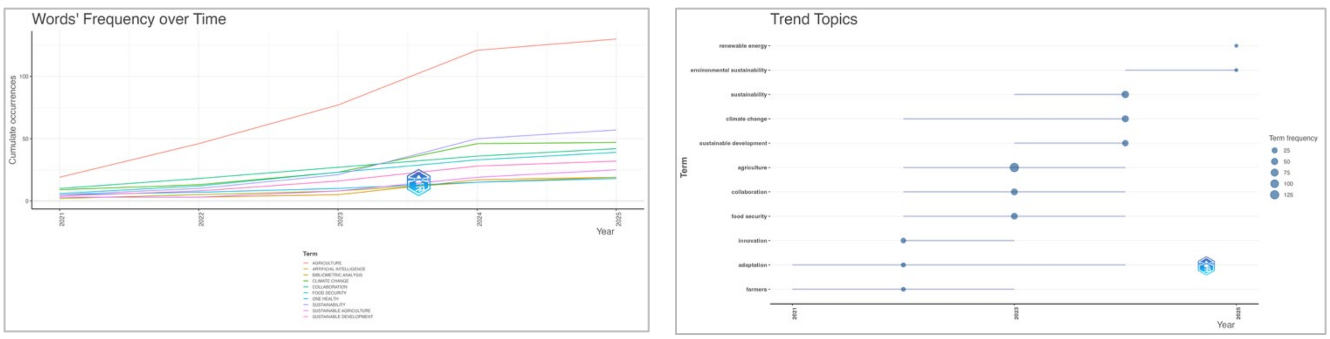

Figure 1. Word frequency over time and Trend topics.

The trend topic analysis (Figure 1) highlights “collaboration” as an emerging theme within the sustainability and food security discourse. While its frequency remains lower than foundational terms like “agriculture” or “sustainability,” its upward trajectory indicates a growing emphasis on stakeholder-driven and systemic approaches to sustainable development (Braun et al., 2023; Walthall et al., 2024).

Hierarchical clustering (Figure 2) and the conceptual structure map derived from Multiple Correspondence Analysis (MCA) further reinforce this trend. “Collaboration” clusters closely with concepts such as “integration,” “management,” and “networks,” suggesting its increasing association with system-level transformation and governance in agri-food systems. Its spatial proximity to terms like “framework,” “performance,” and “technology” also points to an emerging link between collaborative practices and digital transition agendas.

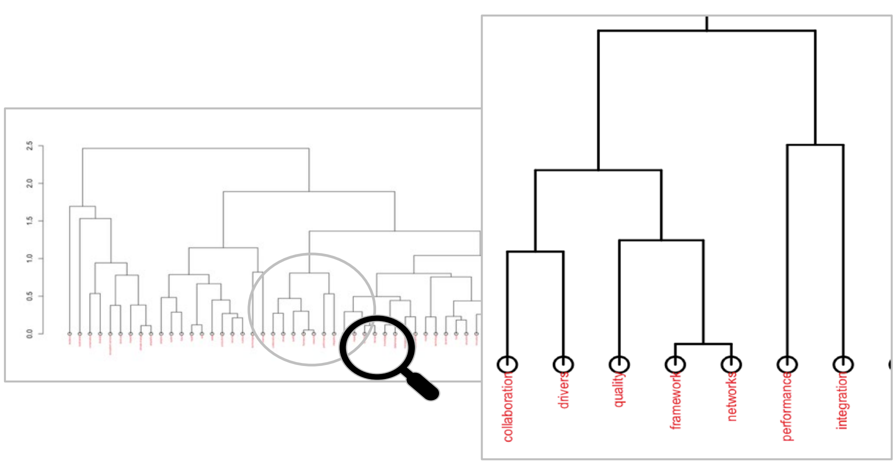

Figure 2. Factorial Analysis results of the reviewed literature.

Insights from the dendrogram and conceptual structure map show that collaboration is increasingly viewed as part of broader systemic innovations in sustainability, governance, and technological integration. *This reinforces the relevance of the present study, which identifies which sustainable agriculture models best enable meaningful stakeholder collaboration.* By linking behavioral collaboration factors with sustainability models, the study offers a structured basis for advancing inclusive and system-oriented agri-food strategies.

2.2 Factors Enabling Collaboration and Sustainable Agriculture Models

Collaboration is increasingly recognized as a critical enabler for addressing systemic challenges in agri-food systems, such as biodiversity loss, soil degradation, and social inequities. Recent studies emphasize its role in supporting collective action, knowledge co-creation, and institutional transformation. Braun et al., (2022, 2023) frame collaboration as an emergent, iterative process fostered through learning networks and boundary work within agri-food value chains. Similarly, (Massari et al., 2023) highlight co-creativity within Living Labs as key to enabling adaptive, design-driven collaboration, while (Walthall et al., 2024) position collaboration as central to agroecological transition, emphasizing horizontal networks and multi-stakeholder engagement. These works collectively call for further research into the structural conditions and facilitation mechanisms that shape effective collaborative dynamics.

Responding to this, the present study aims to assess which sustainable agriculture models most effectively support stakeholder collaboration. The model classification builds on Zhang's (2024) comparative typology, which distinguishes sustainability models by scale, ambition, and systemic focus. To evaluate each model's collaborative potential, the study adopts the behavioral collaboration factors identified by Dania et al. (2018), including trust, information sharing, and goal alignment. Together, these frameworks provide a theoretically grounded and practically applicable basis for analyzing collaboration in complex, multi-actor agri-food systems.

3. Methodology

To evaluate the effectiveness of sustainable agriculture models in facilitating stakeholder collaboration, this study adopts an integrated decision-making framework called *2TL-DAD*, which combines the 2-Tuple Linguistic Model (Martínez et al., 2015), Decision making trial and evaluation laboratory (DEMATEL) (Fontela & Gabus, 1976), and Axiomatic Design (AD) (Suh, 1998). The 2-Tuple model captures linguistic uncertainty in expert judgments, DEMATEL identifies causal relationships among collaboration criteria, and Axiomatic Design assesses the consistency between stakeholder needs and system functionalities. Together, these methods provide a balanced qualitative–quantitative approach suited to complex, multi-actor settings. This section briefly introduces each method along with recent applications relevant to agri-food systems.

3.1 2-Tuple Linguistic Model

The 2TL model is a fuzzy logic-based model, minimizes information loss when converting linguistic data into numerical form (Herrera & Martinez, 2000). It employs a 2-Tuple form of *(s, α)*, where *'s'* is a linguistic label and *'α'* is a numerical value. For the necessary and basic definitions, readers can refer to (Martínez et al., 2015). The leading translation equation of 2TL is given as follows:

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

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 (Martı´nez & Herrera, 2012). 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:

$$TF_{t'}^{t} = \left(S_i^{n(t)}, \alpha^{n(t)}\right) = \Delta\left(\frac{\Delta^{-1}\left(\left(S_i^{n(t)}, \alpha^{n(t)}\right) \times (n(t') - 1)\right.}{n(t) - 1}\right) \tag{2}$$

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

The 2-Tuple Linguistic Model enables precise treatment of qualitative expert judgments by encoding linguistic terms without requiring defuzzification, thus preserving both meaning and accuracy. Its ability to seamlessly convert linguistic input into computable values makes it well-suited for integration with quantitative methods like DEMATEL as used by Gao et al., (2023) and Axiomatic Design as applied in Büyüközkan & Uztürk (2018). This makes it particularly effective for evaluating collaboration in sustainable agri-food systems, where complex, stakeholder-driven criteria demand both interpretability and analytical rigor (Uztürk & Büyüközkan, 2023).

3.2 DEMATEL

The DEMATEL method is a structured approach used to model and analyze complex cause–effect relationships among interrelated criteria (Fontela & Gabus, 1976). Its core logic lies in transforming expert judgments into a visualized system of influences, identifying which factors act as drivers and which are dependent. This enables decision-makers to understand not only the strength of relationships but also the direction of influence within a system.

The basic steps of DEMATEL include: (1) collecting expert evaluations of the direct influence among factors; (2) aggregating these inputs into a single matrix; (3) normalizing the matrix; (4) calculating the total influence matrix; and (5) identifying cause and effect groups by computing prominence and relation scores. The method ultimately provides a clear map of the systemic structure, highlighting key drivers that should be prioritized in decision-making.

In this study, DEMATEL is employed to identify how collaboration criteria influence one another across sustainable agriculture models. Its suitability for complex systems is demonstrated in prior applications, such as Avikal et al., (2022), who used DEMATEL to assess drivers of circular economy implementation in agri-supply chains, and Psychogiou & Tsoulfas, (2024), who applied it to model stakeholder interactions in agri-food systems. By revealing hierarchical relationships and feedback loops among behavioral factors, DEMATEL aligns well with the multi-actor dynamics of sustainable agriculture. When combined with the 2TL, it further enhances methodological rigor by preserving the integrity of expert judgments while enabling robust structural analysis as applied in (Uztürk & Büyüközkan, 2023).

3.3 Axiomatic Design

Axiomatic Design (AD) is a design theory framework that supports systematic decision-making by evaluating the relationship between functional requirements (FRs) and design parameters (DPs) based on two core principles: the independence axiom, which seeks to maintain the independence of FRs, and the information axiom, which minimizes complexity (Suh, 1998). Traditionally applied in engineering and product design, AD ensures that each design parameter satisfies its corresponding function without unintended interactions as applied in (Abdel-Basset et al., 2022; Sezer & Durna Pişkin, 2025; Q. Zhang et al., 2024). In the context of decision-making, AD has been increasingly adapted as an MCDM tool to prioritize alternatives based on how well they fulfill a defined set of requirements as Khandekar & Chakraborty, (2018) applied to choose the most appropriate cotton fiber.

This study adopts AD in a novel way—applying it to the evaluation of sustainable agriculture models by treating collaboration criteria as functional requirements and agriculture models as design alternatives. By doing so, AD enables a structured, logic-based prioritization of models according to their ability to meet stakeholder-driven collaboration needs. The integration of AD with the 2TL enables the application of AD in contexts where expert evaluations are inherently qualitative and expressed in linguistic terms. In this framework, the FRs represent the collaboration behavioral criteria (e.g., trust, information sharing), while the DPs are the sustainable agriculture models being evaluated. To construct the Design Matrix, experts assess the degree to which each agriculture model satisfies each collaboration criterion using linguistic variables. Within the AD phase of the proposed *2TL-DAD* model, expert input was collected through two structured linguistic evaluations. First, for each collaboration criterion (FR), experts were asked: *"What is the minimum level a sustainable agriculture model must achieve for this criterion to be considered adequately satisfied?"* The responses, provided in predefined linguistic terms, were used to define the System Range (SR) for each criterion. Second, for each combination of criterion and model (FR–DP), experts responded to the question: *"To what extent does [Model X] fulfill [Collaboration Criterion Y]?"* These evaluations were also expressed in linguistic terms and aggregated using the 2TL Model. The aggregated results were then converted into triangular fuzzy representations to define the Design Range (DR). The degree of overlap between each criterion's SR and the corresponding model's DR was analyzed to assess whether the model sufficiently meets stakeholder expectations. This process allows for a transparent and linguistically consistent prioritization of sustainable agriculture models based on their capacity to support meaningful collaboration. The following Figure 3 provides the detailed flowchart of the suggested *2TL-DAD* methodology.

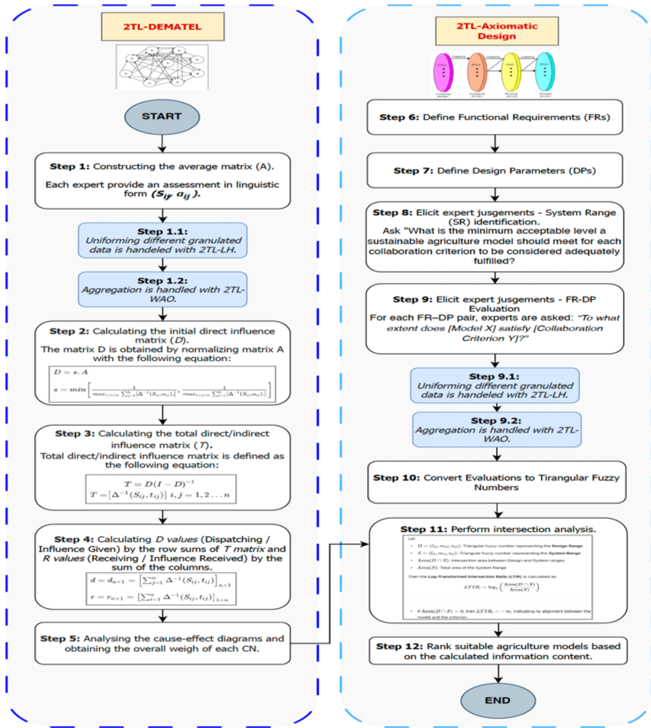

Figure 3. Flowchart of suggested *2TL-DAD* methodology.

4. Case Study

To demonstrate the applicability of the proposed *2TL-DAD* methodology, a case study was conducted to evaluate which sustainable agriculture models most effectively support stakeholder collaboration. *In practice, such prioritization is critical for informing policy decisions and program designs, particularly in contexts where multiple sustainability models exist but institutional and financial resources are limited.* For instance, in local development initiatives, the ability to select between agroecological or regenerative approaches based on their alignment with collaboration needs is essential for ensuring long-term adoption and stakeholder commitment.

The evaluation involved three experts with complementary profiles. Expert 1, a senior specialist with over two decades of experience in sustainable supply chains, employed a detailed 9-point linguistic scale ranging from No Influence (NI) to Perfect Influence (PI). Expert 2, with equivalent seniority and extensive expertise in sustainable agriculture, utilized the same scale to reflect deeper sectoral insight. Expert 3, a mid-career researcher specializing in smart and sustainable agriculture, applied a simplified 5-point scale—NI, LI, MI, HI, PI—appropriate for a more focused and evolving knowledge base. The linguistic assessments were aggregated using the 2TL Model, and the resulting evaluations were analyzed through DEMATEL and AD to examine the interdependencies among criteria and the suitability of each model.

We follow the procedure outlined in Figure 3. First, the defined FRs and DPs, along with their importance weights derived from the 2TL-DEMATEL analysis, are presented in Table 1. Subsequently, Figure 4 illustrates the cause–effect clustering of the FRs, highlighting their directional relationships and influence levels within the system.

Table 1. FRs and DPs defined for the 2TL-DAD application (Dania et al., 2018; Q. F. Zhang, 2024)

FRs	Functional Requirements	Weights	DPs	Sustainable Solutions for Agriculture
FR1	Joint Efforts	0.107	**SS1**	Organic Farming
FR2	Sharing Activities	0.103	**SS2**	Regenerative agriculture (RA)
FR3	Collaboration Value	0.109	**SS3**	Climate-Smart Agriculture (CSA)
FR4	Adaptation	0.087	**SS4**	Carbon-capture agriculture
FR5	Trust	0.109	**SS5**	Nature-based agriculture
FR6	Commitment	0.109	**SS6**	Alternative Food Networks (AFNs)
FR7	Power	0.062	**SS7**	Permaculture
FR8	Continuous Improvement	0.105	**SS8**	Agroecology
FR9	Coordination	0.112		
FR10	Stability	0.097		

Figure 4. Cause-Effect diagram of 2TL-DEMATEL

According to the cause–effect diagram, FR10 (Stability), FR7 (Power), FR3 (Collaboration Value), and FR4 (Adaptation) are positioned in the cause group, indicating that they act as driving factors influencing other collaboration criteria. Among them, FR10 exhibits the highest net influence, highlighting its foundational role in shaping collaborative dynamics. In contrast, FR1 (Joint Efforts), FR6 (Commitment), FR5 (Trust), and FR8 (Continuous Improvement) fall into the effect group, suggesting they are primarily influenced by other factors rather than initiating influence themselves. Meanwhile, FR2 (Sharing Activities) is slightly above the x-axis and categorized as a weak cause, while FR9 (Coordination) lies just below it, indicating a marginal effect role. These borderline positions reflect their intermediary influence within the system. Overall, the results emphasize that system-level drivers such as stability, power, and collaboration value are essential precursors for enabling downstream behaviors like trust, commitment, and joint efforts in sustainable agricultural collaboration (Table 2).

Table 2. Aggregated evaluation matrix of 2TL-AD.

FRs	SRs	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8
FR1	**LAM**	(AHR,-0.22)	(HR, -0.39)	(MR, 0.0)	(LR, 0.0)	(AHR,-0.22)	(HR,-0.39)	(HR, 0.39)	(AHR,-0.22)
FR2	**LAM**	(MR, 0.39)	(AHR, 0.22)	(MR, 0.0)	(LR, 0.39)	(AHR,-0.22)	(HR, 0.39)	(HR, -0.39)	(AHR,-0.22)
FR3	**LAM**	(HR,-0.39)	(HR, 0.39)	(MR, 0.0)	(LR, 0.0)	(AHR,-0.22)	(HR, 0.44)	(HR, 0.39)	(HR, -0.39)
FR4	**LM**	(MR, 0.39)	(VHR,-0.17)	(HR, 0.0)	(MR, 0.0)	(HR, -0.39)	(HR,-0.39)	(HR, -0.39)	(HR, 0.0)
FR5	**LAH**	(HR, -0.39)	(HR, 0.39)	(AHR,-0.22)	(LR, 0.0)	(HR, -0.39)	(HR, 0.44)	(VHR, 0.22)	(HR, 0.0)
FR6	**LAH**	(HR, 0.39)	(AHR, 0.22)	(AHR, -0.22)	(AMR, 0.22)	(HR, -0.39)	(HR,-0.39)	(VHR, 0.22)	(HR, 0.0)
FR7	**LL**	(LR, 0.0)	(LR, 0.0)	(LR, -0.39)	(VLR, -0.22)	(VLR, 0.22)	(LR, 0.0)	(VLR, 0.17)	(LR, 0.0)
FR8	**LM**	(AHR,-0.22)	(HR, 0.39)	(HR, -0.39)	(MR, 0.0)	(HR, 0.0)	(HR, 0.0)	(AHR, 0.22)	(MR, 0.39)
FR9	**LAH**	(HR, -0.39)	(HR, 0.44)	(AHR, -0.22)	(LR, 0.0)	(HR, -0.39)	(HR, 0.44)	(HR, 0.39)	(AHR, 0.22)
FR10	**LM**	(MR, 0.39)	(HR, 0.39)	(MR, 0.0)	(LR, 0.39)	(AHR,-0.22)	(HR,-0.39)	(HR, 0.39)	(HR, 0.0)

The aggregated expert matrix used in the 2TL-AD process is presented above. For each DP–FR pair, information content is calculated based on the intersection area between the aggregated evaluation (Design Range) and the expected performance level (System Range), as illustrated in the subsequent Figure 5. These values are then weighted using the 2TL-DEMATEL importance scores to inform the final ranking of alternatives.

Figure 5. Area intersection of (AH,0.22) and LAM (at least medium) system range.

Table 3. Information content of each alternative.

Imp.	FRs	SRs	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8
0.103	FR1	LAM	2.59	3.50	1.04	9.29	2.59	3.50	0.00	2.59
0.101	FR2	LAM	0.08	0.12	1.04	0.55	2.59	0.00	3.50	2.59
0.105	FR3	LAM	3.50	0.00	1.04	9.29	2.59	0.00	0.00	3.50
0.097	FR4	LM	0.33	0.18	0.33	2.56	7.38	7.38	7.38	0.33
0.104	FR5	LAH	∞	0.00	∞	∞	∞	0.00	0.00	0.97
0.105	FR6	LAH	∞	0.16	∞	3.18	∞	∞	0.00	0.97
0.087	FR7	LL	2.97	2.97	∞	∞	1.72	2.97	2.24	2.97
0.104	FR8	LM	2.59	7.38	7.38	2.56	0.33	0.33	0.11	0.33
0.105	FR9	LAH	∞	0.00	∞	∞	∞	0.00	0.00	0.16
0.101	FR10	LM	0.33	7.38	1.04	1.12	2.59	7.38	7.38	0.33
	SUM		21.7					20.6	14.7	
	Rank		3					2	1	

The final matrix presents the log-transformed information content values calculated for each FR-DP pair. Infinity values (∞) indicate that no intersection exists between the Design and System Ranges for a given criterion (Table 3), meaning that the corresponding sustainable agriculture model fails to meet the minimum required performance level. In line with the AD logic, such alternatives are excluded, as full coverage across all collaboration criteria is a prerequisite for further consideration.

Following this elimination, three alternatives remain: SS2 (Regenerative Agriculture), SS7 (Permaculture), and SS8 (Agroecology). Among them, the model with the lowest total information content is preferred. These values can optionally be weighted by the 2TL-DEMATEL-derived criterion importance scores; however, both the weighted and unweighted rankings yield the same order, underscoring the internal consistency of the results. Further analysis about weighting will be provided in discussion section. These findings suggest that agroecology, permaculture, and regenerative agriculture exhibit the strongest alignment with the identified collaboration dimensions, making them particularly suitable for implementation in participatory, stakeholder-driven sustainability strategies.

5. Results and Discussion

As noted in the previous section, the final ranking of sustainable agriculture models remained unchanged regardless of whether the information content values were weighted by FR importance scores. This result underscores the robustness and internal consistency of the proposed *2TL-DAD* framework. However, to assess the model's responsiveness *to shifting strategic priorities—which is critical for real-world decision-making where governments, cooperatives, or private organizations may emphasize different collaboration goals*—a sensitivity analysis was conducted.

In this analysis, each FR was assigned a dominant weight in turn, creating ten distinct scenarios (Case 1–10). This approach simulates real-world decision-making contexts where specific collaboration dimensions—such as trust, power, or adaptation—may be emphasized due to institutional strategy or policy agendas. The goal was to assess whether these shifts in priority would alter the overall ranking of sustainable agriculture models.

Table 4. Sensitivity analysis for 2TL-AD results

	Only Inf. Value	**Weighted Information Value**		**Case1 (FR1)**	**Case2 (FR2)**	**Case3 (FR3)**	**Case4 (FR4)**	**Case5 (FR5)**
		DEMATEL Weighted Average Values	**DEMATEL Geometric Average Values**					
SS2	3	3	3	3	1	2	2	2
SS7	2	2	2	1	3	1	3	1
SS8	1	1	1	2	2	3	1	3
	Case6 (FR6)	**Case7 (FR7)**	**Case8 (FR8)**	**Case9 (FR9)**	**Case10 (FR10)**	**# of Ranked 1**	**# of Ranked 2**	**# of Ranked 3**
SS2	3	3	3	3	3	1	3	9
SS7	1	1	2	2	2	5	6	2
SS8	2	2	1	1	1	7	4	2

As summarized in the Table 4, SS8 (Agroecology) consistently ranked first in 7 of 10 cases, demonstrating strong alignment with a wide range of FR priorities. SS7 (Permaculture) ranked first in 2 cases and showed stable performance, especially when criteria like commitment (FR6) or collaboration value (FR3) were emphasized. In contrast, SS2 (Regenerative Agriculture) ranked first in only one case and ranked third in 9 scenarios, indicating its lower robustness under shifting strategic focus. *Agroecology and Permaculture are particularly resilient options, capable of maintaining their collaborative advantage even under shifting stakeholder priorities.*

Importantly, while the *2TL-DAD* methodology demonstrates robustness, it must be acknowledged that the FR importance weights were derived from evaluations conducted by a limited panel of Turkish experts. Thus, the prioritization reflects the contextual understanding, sectoral experience, and socio-economic background of these experts. It does not claim to offer a universally valid solution. In different settings or with different decision-makers, both the prioritization of FRs and potentially the system range boundaries could vary, reflecting divergent collaboration dynamics, local needs, or policy objectives.

Nevertheless, the ability of the proposed methodology to withstand these strategic changes without major alterations in final prioritizations proves its replicability and robustness. Furthermore, by integrating 2TL-DEMATEL and AD, the proposed model offers a structured, data-driven, and transparent procedure for strategy generation in sustainable agriculture, enabling more informed and adaptable decision-making.

Beyond the overall model ranking, the analysis also offers important insights into the strategic prioritization of specific collaboration criteria (FRs). According to the 2TL-DEMATEL results, FR10 (Stability), FR7 (Power), FR3 (Collaboration Value), and FR4 (Adaptation) emerged as key driving factors within the system, indicating their foundational role in enabling other collaborative behaviors. These findings are consistent with Dania et al. (2018), who emphasized the systemic importance of factors such as stability and power for ensuring long-term relationship management and coordination across stakeholders. Similarly, Collaboration Value and Adaptation were highlighted by Dania et al. (2018) as critical to fostering flexible, resilient partnerships and navigating diverse stakeholder needs. Conversely, FR1 (Joint Efforts), FR5 (Trust), FR6 (Commitment), and FR8 (Continuous Improvement) were classified as effect factors, typically resulting from a strong collaborative environment—again echoing Dania et al.'s findings, which positioned trust and commitment as outcomes that flourish under favorable structural and relational conditions.

In line with these findings, it is informative to compare our results with Zhang (2024), who similarly identified Agroecology and Permaculture as the most transformative models within sustainable agrifood systems. Zhang emphasizes Agroecology's role in promoting ecological sustainability, food sovereignty, and social justice, while highlighting Permaculture's holistic, design-based approach to resilient system building. Our results strongly align with these conclusions: Agroecology (SS8) consistently emerged as the most robust model, with Permaculture (SS7) also demonstrating strong adaptability across varying strategic priorities. However, Zhang also notes context-specific challenges, such as Permaculture's scalability and potential political resistance to Agroecology's transformative agenda. These observations further validate the importance of sensitivity analyses, as applied in this study, to ensure practical relevance across diverse policy settings.

Thus, the *2TL-DAD* framework not only confirms the collaborative strength of Agroecology and Permaculture but also offers a robust, adaptable decision-support tool for tailoring sustainable agriculture strategies to varying socio-economic and political contexts.

6. Conclusions

This study introduced the 2TL-DAD framework to evaluate which sustainable agriculture models best enable stakeholder collaboration, combining 2-Tuple Linguistic modeling, DEMATEL, and Axiomatic Design. Results showed that Agroecology and Permaculture consistently ranked highest across scenarios, reflecting strong alignment with key collaboration drivers such as stability, power, and adaptability.

The proposed approach offers a robust, flexible tool for decision-making under uncertainty and context-specific priorities. Future research may investigate the sensitivity of Design Ranges (DRs), which can vary across stakeholder groups and policy contexts, and extend the model using alternative MCDM techniques to differentiate top-ranked models based on non-collaboration criteria such as cost, scalability, or environmental impact.

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Biography

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She teaches Advanced Mathematics to first-year students and Data & Business Analytics to senior undergraduates. Her research spans smart systems, linguistic and fuzzy multi-criteria decision-making (MCDM), circular economy, climate risk evaluation, and smart agriculture technologies. With a strong focus on sustainability, digital transformation, and system design under uncertainty, her recent work applies innovative methodologies—such as Fermatean and 2-tuple fuzzy logic—to evaluate technologies, inform policy, and guide strategic planning in the context of Industry 5.0 and beyond.