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Hybrid AHP-DEMATEL Model for Prioritizing Key Resilience and Sustainability Drivers and Controllers in Agri-Food Supply Chains

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ABSTRACT

Agri-food systems are fundamental at the intersection of agriculture and industrialization, playing a crucial role in global food production and distribution. However, each agri-food supply chain (AFSC) has unique characteristics, posing the challenge of identifying tools and strategies that can be adapted to diverse contexts. Sustainability has now become a priority, driven by increasing consumer awareness of the environmental impact of agricultural and industrial practices. This shift has transformed sustainability from a trend into a necessity to ensure efficient and resilient operations. Achieving this requires effective cooperation across all supply chain links, promoting the integration of economic, social, political, and environmental aspects. This study aims to identify and prioritize the key drivers and enablers of resilience and sustainability in AFSCs. Through a systematic literature review (SLR), drivers were grouped with their respective enablers, creating a framework to assess their impact on the performance of each supply chain component. The Analytical Hierarchy Process (AHP) was used to assign weights to the drivers, while the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was applied to evaluate interactions between variables and establish a ranking of their relative influence. The results revealed that the driver "Evolution of Agricultural Systems" had the highest weighting, followed by "Water Footprint." Regarding enablers, the highest-scoring factors were "Redesign and Coordination of Operations" and "Collaboration Across Supply Chain Links." These findings provide a solid foundation for strategic decision-making to enhance the sustainability and resilience of AFSCs.

1. INTRODUCTION

The agri-food system plays a crucial role in agriculture and food industrialization in many countries [1]. In this context, the agri-food supply chain (AFSC) is structured through a network of corporate suppliers, framed within an agroindustrialization model where large-scale agriculture predominates [2]. Optimizing efficiency levels, productivity, and consolidating economies of scale becomes an essential factor in ensuring the sustainability and competitiveness of the sector [1, 3].

Currently, an agri-food system aims to provide a sustainable supply of healthy food. Consequently, data provided by industrial systems with digitized supply chains play a key role in facilitating the transformation of the agricultural system into a resilient, sustainable one, ensuring global food security [4, 5]. As a result of globalization, disruptions along Supply Chains (SC) have made them unsustainable. Some of the issues they present include increased waste, indiscriminate consumption of non-renewable resources, and environmental pollution, which in turn leads to climate change [6, 7].

Throughout the AFSC, a multitude of waste is generated, which translates into significant economic losses for its actors [8]. However, the consequences are not limited to monetary losses; they also have a notable environmental impact [9], not to mention the challenges presented to human health, directly affecting society [10]. This is why conducting a thorough analysis of the supply chain and the proper implementation of renewable resources throughout the AFSC becomes a strategic approach for managing food waste [11, 12].

AFSCs are strongly connected with Small and Medium Enterprises (SMEs), which is why the environmental approach of the supply chains is analyzed at various levels to prevent disruptions along them. Environmental practices must be sustainable, from the first link in the chain to the consumer. The environmental awareness of consumers motivates them to assess the food life cycle, as well as conduct a thorough analysis of the food production process. This enables the Supply Chain Management (SCM) to maintain a positive impact related to environmental sustainability [13, 14].

There are fundamental pillars for managing food waste, such as assigning value to waste to use it as bioactive compounds for the agricultural system. Reutilization of products is another key pillar in the system. However, for the successful implementation of these foundations, a vision oriented towards sustainability is necessary. This is why, today, the circular economy (CE) plays an important role in supply chains [15, 16].

Proper food waste management drives the effective utilization of the benefits offered by the CE at each link of the supply chain. Therefore, the use of clean technologies allows companies to transform their operations, making them circular and generating a positive impact on society, the environment, and the economy [17]. Bioactive substances, biofuels, waste as raw materials for other systems, biopolymers, biochemicals, bioenergy, and even food additives, among others, are products into which agro-food waste can be transformed. This is the potential of the CE, which aims to reduce the environmental impact of a system while ensuring the protection of non-renewable resources [18].

However, for processes to be directed towards sustainable innovation, it is necessary to develop sustainable policies and regulations that connect with society, fostering development within the socio-ecological system of agriculture [19]. The implementation of sustainability enhances the competitive level of companies, and the application of circular operations within the internal levels of the supply chain and society provides exponential competitive advantages, leading to market expansion [20].

The sustainability of AFSCs represents a significant challenge, as it involves ensuring equitable benefits for all actors involved in the logistics network [1]. Despite the presence of multiple barriers that limit its development, there are key determinants—classified as controllers and drivers—that enhance the efficient performance of the chain. Identifying and analyzing these elements through systematic research approaches is essential for understanding their interrelationships and their impact on system optimization. In this context, recognizing these factors enables the various actors within the AFSC to design and implement strategies that strengthen its operation, thereby ensuring the delivery of products that meet market expectations and needs in a sustainable and efficient manner.

AFSCs are characterized by their dynamism and complexity, as products can originate from both large agricultural operations and small farms, introducing variability in their operations. Each actor in the chain adopts differentiated strategies and practices, making standardization difficult and posing challenges for the system's sustainability and efficiency. Nonetheless, the fundamental goal of AFSCs remains to guarantee the delivery of quality products to consumers. Throughout the literature, multiple studies have been developed on the functioning and optimization of these chains [19, 21, 22]; however, a gap remains in the identification and prioritization of methodological tools that allow for the evaluation of the key controllers and drivers of sustainability and resilience in different agro-food contexts. Promoting sustainability in AFSCs involves a synergy among social, ecological, and economic factors, in addition to considering the system's resilience to disturbances [8]. In this regard, the assessment of AFSC sustainability has become a rapidly developing area of research aimed at strengthening decision-making at both local and global levels, facilitating the identification of key criteria and interactions between society and nature [23].

In this context, the present research aims to identify and prioritize the key controllers and drivers of resilience and sustainability in AFSC. Through a systematic literature review (SLR), the study seeks to answer the following research questions: What controllers are applicable to an AFSC? Is it possible to prioritize the drivers through an analytical assessment? To address these questions, three main objectives are established: i) to identify the controllers and drivers that promote the sustainability of the AFSC; ii) to evaluate, using the Analytical Hierarchy Process (AHP), the consistency and weighting of the controllers in order to strengthen the sustainability of the chain; and iii) to prioritize the identified drivers using the DEMATEL method. The research adopts a hybrid methodological approach, utilizing AHP for assigning weights to the controllers and DEMATEL for evaluating and prioritizing the drivers, with the aim of establishing consistent relationships among the selected elements and fostering more informed and efficient decision-making.

2. RESEARCH METHODOLOGY

For the development of this research, a mixed methodological approach was adopted, combining a SLR with a hierarchical analysis of the determining factors in AFSC. In the first phase, an SLR was conducted following guidelines established in the literature [24, 25], with the aim of identifying the main controllers and drivers that influence the efficiency and sustainability of AFSCs.

Subsequently, in the second phase of the study, the AHP and DEMATEL methods were employed to analyze the hierarchical structure and causal interdependencies between the identified factors. This methodological combination not only enabled a structured classification of the key elements but also facilitated the evaluation of their relationships of influence, thus providing a robust analytical framework for the formulation of strategies to optimize the management of AFSCs.

2.1 Systematic literature review

In agricultural systems (AS), the interaction among the actors involved enhances resilience capacity. An AS is the result of understanding the roles that each individual plays within it, enabling greater development of skills, knowledge acquisition, and increased trust among the participants. This leads to improvements in both the economic and social aspects, which in turn affect the evaluation of diverse perspectives among farmers concerning environmental sustainability and SC performance [2].

AFSCs face constant challenges due to product shortages and disruptions in their flow, causing significant environmental impacts. In this context, CE proposes strategies such as recycling, extending product lifecycles, reusing, and maximizing the value of resources [26], facilitating more efficient and sustainable management of AFSCs. Implementing these principles requires that each link in the chain recognizes the value of the products they deliver and optimizes the use of raw materials, including the waste generated in previous stages, thereby promoting process redesign, enhancing social responsibility, and increasing environmental sustainability. As a result, adopting a strategy based on CE improves operational efficiency and the resilience of AFSCs, optimizing their performance and reducing environmental impacts.

Various events have disrupted SCs, prompting a strong motivation for innovation [27]. This is why flexibility in AFSCs suggests that each link in the chain (farmers, producers, food industry, market, and consumers) must develop and implement technology at different stages of the SC, adding value to AFSCs and leading to an eco-innovative perspective where competitive advantages become evident [28].

The Internet of Things (IoT) enhances productivity and sustainability in the agro-food system [29, 30]. With IoT, numerous aspects could be better managed, such as real-time traceability in the SC, considering more convenient factors when making decisions about product care and harvesting, and even using technology in the field to monitor climate conditions more frequently [31].

AFSCs also face challenges in product quality due to perishability [32]. Therefore, quality management throughout the AFSC plays a significant role. For this reason, the design of the SC is considered, where the use of blockchain (BC) is promoted as it fosters transparency within the regulatory system, building trust between producers and consumers. It also allows consumers to make decisions based on accurate information regarding SC traceability, thereby adding value to the system [33].

The research was based on a SLR to identify the key drivers and controllers of sustainability in AFSCs. The literature search was conducted across three high-impact academic databases: Scopus, ScienceDirect, and Web of Science (WoS), chosen for their relevance in the field of sustainability and AFSC management. The search period was limited to articles published between 2020 and 2024. Additionally, the search was restricted to articles written exclusively in English, as this is the most common language in international scientific literature. Various combinations of keywords were used to optimize the relevance and comprehensiveness of the search in the SLR. The main keywords and their combinations covered the key topics of the research, including "agricultural supply chain," "sustainability," "drivers and controllers," "agro-industrialization," "supply chain sustainability," "environmental impact," and "water footprint" to identify relevant drivers and controllers. About sustainability in the agricultural supply chain, terms such as "agricultural systems," "supply chain," "agroecosystems," "biodiversity conservation," "organic farming," "water usage," and "life cycle assessment" were used. Furthermore, combinations related to analytical methods such as "AHP", "DEMATEL", "analytical hierarchy process," "decision-making in supply chains," and "multicriteria decision analysis" were included. Specific search phrases included "sustainability and agricultural supply chain," "drivers of sustainability in supply chains," and "controllers of agro-industrial systems," aiming to comprehensively cover key sustainability aspects and methods applied in decision-making within AFSCs.

Initially, 850 potentially relevant articles were identified, distributed across 410 from Scopus, 270 from ScienceDirect, and 170 from Web of Science. After removing duplicates and conducting a preliminary screening of titles and abstracts, predefined inclusion and exclusion criteria were applied. Inclusion criteria required studies to be published between 2020 and 2024, written in English, explicitly address sustainability, resilience, or risk management within AFSCs, and employ analytical frameworks or empirical models. Exclusion criteria included studies not peer-reviewed, those belonging to grey literature (e.g., theses or institutional reports), conceptual papers lacking a robust methodological approach, and those unrelated to the agri-food context. Additionally, to ensure transparency and quality in the selection process, a quality assessment was conducted using a structured rubric considering (i) methodological rigor, (ii) thematic relevance to AFSCs, and (iii) analytical depth. Only studies scoring above 70% in this evaluation were included. As a result of this rigorous process, the final sample was reduced to 320 studies, of which 181 directly addressed the research objectives. After a second evaluation, 34 high-quality studies were selected for in-depth analysis, ensuring alignment with the topic and methodology of the SLR. The findings from this selection provided the empirical and conceptual foundation for identifying 18 key drivers and controllers of sustainability in AFSCs, which are presented in Table 1.

Table 1. Drivers and controllers

No.	Drivers and Controllers	Description	Source
1	Agricultural Systems Assessment	Study of environmental, agricultural, and food dimensions.	[3, 13]
2	Organic Farming Management	Biodiversity maintenance and agroecosystem conservation.	[14, 34, 35]
3	Redesign and Coordination of Operations	Strategic level of AFSC. Economic, social, and environmental aspects.	[36]
4	Water Footprint	Agricultural sector measurement and impact of water resources.	[37]
5	Volumetric Water Footprint	Minimize impact from water use.	[38]
6	Life Cycle	Water footprint assessment based on product life cycle.	[39]
7	Resilience in the Agro-food System	Ability to balance socioeconomic aspects and natural resources.	[40]
8	Collaboration Between Links	Joint planning and industrial symbiosis.	[1, 41]
9	Customer Commitment	Strengthening business performance with the customer.	[29, 42]
10	Blockchain	Transparency, efficiency, and sustainability in supply chains.	[2, 27]
11	Electronic Data Interchange	Increase efficiency in the supply chain.	[43, 44]
12	Security	Transparency, traceability, and a solid environment for supply chains.	[45, 46]
13	Environmental Sustainability	Relationship of farmers with environmental impact.	[9, 47]
14	Social Responsibility	Sustainable performance and food safety.	[10, 21]
15	Waste Reduction	Reduction of cross-contamination and preservation of sustainability in the supply chain.	[8, 21]
16	IoT Application	Improved logistics in AFSCs.	[4, 5, 30, 48]
17	Network Layer	Enhanced performance of AFSCs.	[49, 50]
18	Process and Activity Integration	Grouping of design, development, and logistics.	[32, 51]

Notes: The sources referenced in the table correspond to the respective studies and articles from which the identified drivers and controllers were derived.

Subsequently, the grouping and structured coding of the drivers and controllers were carried out in three levels, allowing for an accurate classification of the key factors. Based on this structure, a systematic methodology was developed aimed at applying the hierarchical process, ensuring a rigorous and consistent analysis of the relationships between the identified elements (Figure 1).

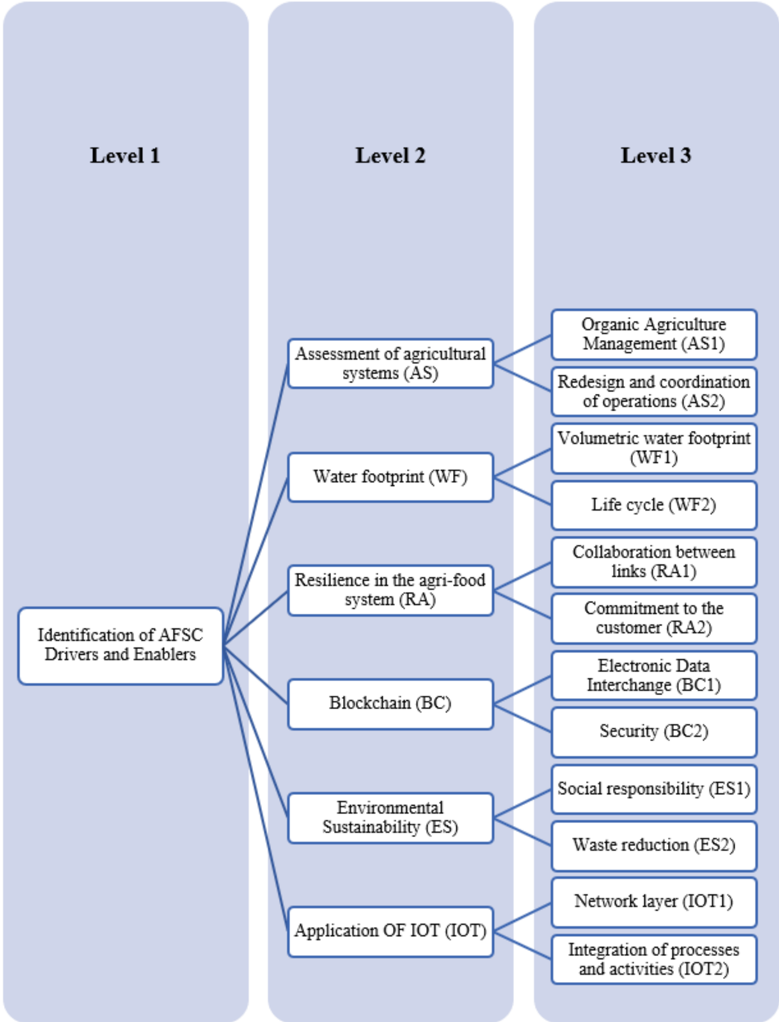

Figure 1. Framework for grouping drivers and controllers

2.2 Analytical Hierarchy Process (AHP)

AHP is a widely used multicriteria decision-making (MCDM) method for evaluating and prioritizing criteria in complex decision-making scenarios [52]. Its application allows a problem to be broken down into a hierarchical structure and assigns relative weights to the considered factors, facilitating a structured and objective analysis [51, 53].

For the implementation of the AHP method in this study, the following steps were followed:

Step 1. Definition of inclusion and exclusion criteria: The elements to be prioritized were established through a SLR, selecting the most relevant drivers.

Step 2. Construction of the comparison matrix: A pairwise comparison matrix was developed using Saaty's nine-point scale (Table 2), which allows for quantifying the relative importance of each driver [54].

Step 3. Normalization of the matrix: The matrix was normalized by dividing each driver's weight by the sum of its corresponding column.

Step 4. Determination of the weight of each driver: The relative weight of each driver was calculated as the average of the values obtained in the normalized matrix.

Table 2. Pairwise comparison scale

Numerical Scale	Verbal Scale	Explanation
1	Equally Important	Two elements contribute equally to the objective.
3	Moderately Important	Slight preference of one element over the other.
5	Strongly Important	Strong preference of one element over the other.
7	Very Strong or Demonstrated	Much stronger preference of one element over the other.
9	Extremely Strong	Clear and absolute preference of one element over the other.
2, 4, 6, 8	Intermediate	Intermediate values to refine the comparison.

Step 5. Evaluation of consistency: The validity of the experts' judgments was assessed by calculating the Consistency Ratio (CR), defined as CR = CI/RI, where *CI* denotes the Consistency Index and *RI* the Random Index. A pairwise comparison matrix is considered acceptably consistent when CR < 0.1. Twelve international experts from

Mexico, Spain, Ecuador, and Venezuela participated in the analysis. Half of the panelists held doctoral degrees, and the remaining 50% held master's degrees. All experts had a minimum of five years of experience in applying MCDM methods. Their academic and professional backgrounds span key areas such as industrial engineering, SCM, and agri-food sustainability, including specialists in risk management and sustainable supply chains. The interdisciplinary and international composition of the panel contributed to the robustness, credibility, and objectivity of the weighting process.

2.3 Decision-Making Trial and Evaluation Laboratory (DEMATEL) method

The DEMATEL method has become an effective tool for analyzing complex systems, allowing for the management of large volumes of variables and quantifying their causal interactions [55]. Its application facilitates the identification of influence relationships between the analyzed factors, providing an analytical framework to evaluate their impact on the system's structure.

One of the main reasons for adopting the DEMATEL method in this study is its ability to model bidirectional relationships between factors, enabling a deeper understanding of the interaction dynamics within a hierarchical system [56]. Furthermore, its matrix-based approach allows for the classification of factors into causal and effect groups, aiding in problem planning and visualization through graphical representations that highlight causal relationships between elements [57].

Table 3. Linguistic influence scale

Influence Score	Linguistic Term
0	No influence
1	Low influence
2	Medium influence
3	High influence
4	Very high influence

For the application of the DEMATEL method, the following methodological steps were followed [58, 59]:

Step 1. Construction of the initial matrix: The evaluation matrix was established using a linguistic influence scale (Table 3), where experts assigned values based on the degree of relationship between the factors [60].

Step 2. Calculation of the direct influence matrix (X): This is obtained by multiplying the minimum value of the initial matrix by each element in the matrix.

Step 3. Construction of the identity matrix (I): A matrix is generated in which the main diagonal contains values of 1, and the rest of the elements are 0.

Step 4. Determination of the total relationship matrix (T): This is calculated using the equation $T = X - (I - X)^{-1}$, where all interactions between the factors are represented.

Step 5. Calculation of the R and C vectors: R is obtained as the sum of the values in each row of the total matrix, representing the influence exerted by each factor. Likewise, C is the sum of each column, reflecting the influence received by each factor.

Step 6. Determination of the importance and influence of the factors: The value of R+C is calculated, indicating the relevance of each factor in the system, while R−C helps distinguish causal factors from effect ones.

3. RESULTS

3.1 AHP Method Evaluation and Driver Prioritization

The AHP method evaluated each driver using a matrix where the drivers are listed in the left column with their respective codes, and the horizontal axis only includes the driver codes for didactic purposes. The main diagonal is characterized by being represented with the number 1, as it reflects the intersection between drivers of equal importance. Next, the normalized matrix can be seen, with values resulting from dividing the numerical value of each driver by the total sum of each column.

Once the normalized matrix was constructed, the average of each value was used to obtain the weights for each driver. These weights indicate that the driver "Evolution of Agricultural Systems (AS)" is the most important, with the highest weight (0.314). The second most important driver is "Water Footprint (WF)" with a weight of 0.231, followed by "Resilience in the Agro-food System (RA)" in third place with a weight of 0.115. In fourth place is "Block Chains (BC)" with a weight of 0.093, while "Environmental Sustainability (ES)" ranks fifth with a weight of 0.075. The sixth driver, "IoT Application (IOT)," has a weight of 0.034 (Table 4).

Table 4. AHP method weighting matrix

Drivers	AS	WF	RA	BC	ES	IOT	Normalized Matrix						Weight	CR=CI/RI
AS	1	3	3	5	5	5	0.441	0.608	0.304	0.063	0.260	0.208	0.314	**0.094**
WF	1/3	1	5	5	5	5	0.147	0.203	0.507	0.063	0.260	0.208	0.231	
RA	1/3	1/5	1	3	3	5	0.147	0.041	0.101	0.038	0.156	0.208	0.115	
BC	1/5	1/5	1/3	1	5	3	0.088	0.041	0.034	0.013	0.26	0.125	0.093	
ES	1/5	1/3	1/3	1/5	1	5	0.088	0.068	0.034	0.003	0.052	0.208	0.075	
IOT	1/5	1/5	1/5	1/3	1/5	1	0.088	0.041	0.020	0.004	0.010	0.042	0.034	
TOTAL	2.27	4.93	9.87	79	19.2	24								

Notes: The table presents the values obtained using the AHP method to evaluate the drivers. The calculated consistency ratio (CR) is 0.094, indicating consistency in the evaluation (CR < 0.1).

To evaluate the consistency of the criteria weighting, the CR was calculated, resulting in a value of 0.094. Since this value is below 0.1, it is concluded that the evaluation of the criteria is consistent (Table 4).

3.2 Evaluation of drivers using DEMATEL method

Using the DEMATEL method, a matrix was constructed to reflect the importance and influence of the drivers (Table 5). The first column of the table presents the twelve codes corresponding to each driver, while the following columns display the values of R (influence exerted), C (influence received), relative importance within the model (R+C), and the influence of other factors on the driver (R-C). These values allow for establishing the hierarchy of the drivers based on their impact on the analyzed system. In this study, a threshold of 0.38 was used, which helps differentiate between drivers with greater influence and those with a lesser impact on the model's dynamics.

Table 5. Matrix of factor importance within the model (R+C) and influence of other factors on the factor (R-C)

Drivers	R	C	R+C	R-C	Ranking	Threshold Value
AS1	4.072	5.383	9.455	-1.311	5	0.38
AS2	5.517	5.128	10.646	0.389	1	
WF1	3.689	3.870	7.559	-0.181	12	
WF2	4.062	3.661	7.723	0.402	10	
RA1	4.824	5.545	10.369	-0.720	2	
RA2	4.911	4.920	9.831	-0.009	4	
BC1	4.359	4.348	8.707	0.012	8	
BC2	4.375	3.848	8.223	0.527	9	
ES1	4.752	4.607	9.359	0.145	7	
ES2	5.296	4.859	10.155	0.437	3	
IO1	4.037	3.600	7.637	0.436	11	
IO2	4.623	4.750	9.374	-0.127	6	

Notes: The threshold of 0.38 was set to identify the most influential drivers, being more restrictive than the minimum range of 0.35 to 0.40.

The 0.38 threshold, more restrictive than the minimum commonly reported in the literature (0.35 - 0.40) [55, 57, 59], aids in identifying the drivers with the highest impact on the system. Values close to 0.35 still reflect moderate influence, but may not be decisive enough to be considered causal drivers. This threshold, being stricter than traditional ones, ensures a more accurate and reliable approach in strategic decision-making within AFSCs, prioritizing factors that have a more significant systemic impact.

From the evaluation matrices completed by the 12 international experts, the values of exerted influence (R), received influence (C), prominence (R+C), and net influence (R–C) were derived for each of the selected drivers, with the results summarized in Table 5. By applying the 0.38 threshold, five drivers with significantly high systemic impact were identified. This threshold was validated through a sensitivity analysis that confirmed its robustness and applicability in this study, ensuring more precise decision-making aligned with best practices in optimizing AFSCs.

3.2.1 Key drivers in the model

The hierarchy of the drivers, based on the R+C values, allowed for the identification of the most systemically relevant factors:

AS2 - Redesign and coordination of operations (R+C = 10.646). This driver is the most influential in the model, highlighting its central role in optimizing processes and operational efficiency within the supply chain. Its positive R-C value (0.389) indicates that it not only receives influence from other factors but also has a high capacity to generate systemic changes.

RA1 - Review of agreements and policies (R+C = 10.369). This driver stands out for its role in aligning regulations and policies, ensuring the resilience and stability of the AFSC.

ES2 - Sustainable strategies in processes (R+C = 10.155). Its relevance lies in its impact on implementing sustainable practices, which enhances the efficiency of the agro-food system and aligns it with environmental sustainability criteria.

RA2 - Restructuring of trade agreements (R+C = 9.831). This driver emphasizes the need to adjust and renegotiate contracts to optimize relationships within the supply chain.

AS1 - Production efficiency management (R+C = 9.455). This highlights the importance of continuous improvement in production processes as a key factor for the sector's competitiveness.

These five drivers represent the strategic pillars of sustainability in the AFSC, as they are strongly interconnected with other system elements and have the potential to generate significant positive impacts on the supply chain.

3.2.2 Moderate impact drivers

Drivers with intermediate R+C values indicate strategic relevance within the system, though with a lesser degree of influence on the overall structure:

IO2 - Organizational innovation implementation (R+C = 9.374). Its impact is linked to modernizing processes and incorporating technology in agro-food management.

ES1 - Environmental regulations application (R+C = 9.359). This represents a fundamental element for regulatory sustainability, ensuring compliance with environmental standards in the AFSC.

BC1 - Consumer welfare practices (R+C = 8.707). This reflects the need to strengthen food security and ensure nutritional quality in agro-food products.

BC2 - Development of value-added products (R+C = 8.223). Its relevance lies in diversifying the offering and differentiating products, which contributes to the economic sustainability of the system.

These drivers play a complementary role in the model and can enhance strategic factors through synergies within the AFSC.

3.2.3 Drivers with lower impact in the model

Factors with lower R+C values show a more limited influence on the system's dynamics; however, their consideration remains relevant for a comprehensive view of the model:

WF2 - Consumer welfare factors (R+C = 7.723). Its positive R-C value (0.402) indicates that, although its overall impact is smaller, it still exerts influence on other factors within the system.

IO1 - Organizational innovation in internal processes (R+C = 7.637). Its ranking suggests that while internal innovation is important, its effect on the global AFSC structure is less significant.

WF1 - Volumetric water footprint (R+C = 7.559). Ranked last, indicating its limited direct impact on the supply chain dynamics. However, its inclusion in the analysis is key for future environmental mitigation strategies and water use efficiency.

Although these drivers have lesser relevance in the model, their role in the sustainability of the AFSC should not be underestimated, as they may serve as enabling elements for broader strategies.

3.2.4 Implications of the results

The findings of this study accurately identify the strategic drivers that should be prioritized in decision-making within the AFSC. The application of the DEMATEL method has helped distinguish between highly influential factors and those with less systemic impact, enabling the design of more effective and focused strategies.

The results highlight that AS2, RA1, and ES2 are the most relevant drivers for strengthening sustainability in the AFSC. Therefore, it is recommended that both policymakers and agro-food sector actors focus their efforts on these key factors.

Furthermore, drivers with moderate and low impact, such as WF1 and IO1, can play a secondary but complementary role in implementing sustainability and operational efficiency strategies. This reinforces the need for an integrated approach in policy formulation and AFSC management.

Overall, these findings provide an empirical basis for prioritizing strategies within the AFSC, offering a replicable framework for other agro-food contexts and contributing to more efficient and sustainable sector management.

Figure 2 shows the causal diagram of the model's drivers, represented on a Cartesian plane. In this graph, the drivers above the X-axis are causal drivers, meaning their R-C value is positive. These drivers have an impact on other elements of the system, suggesting that they have a causal relationship with other factors in the model.

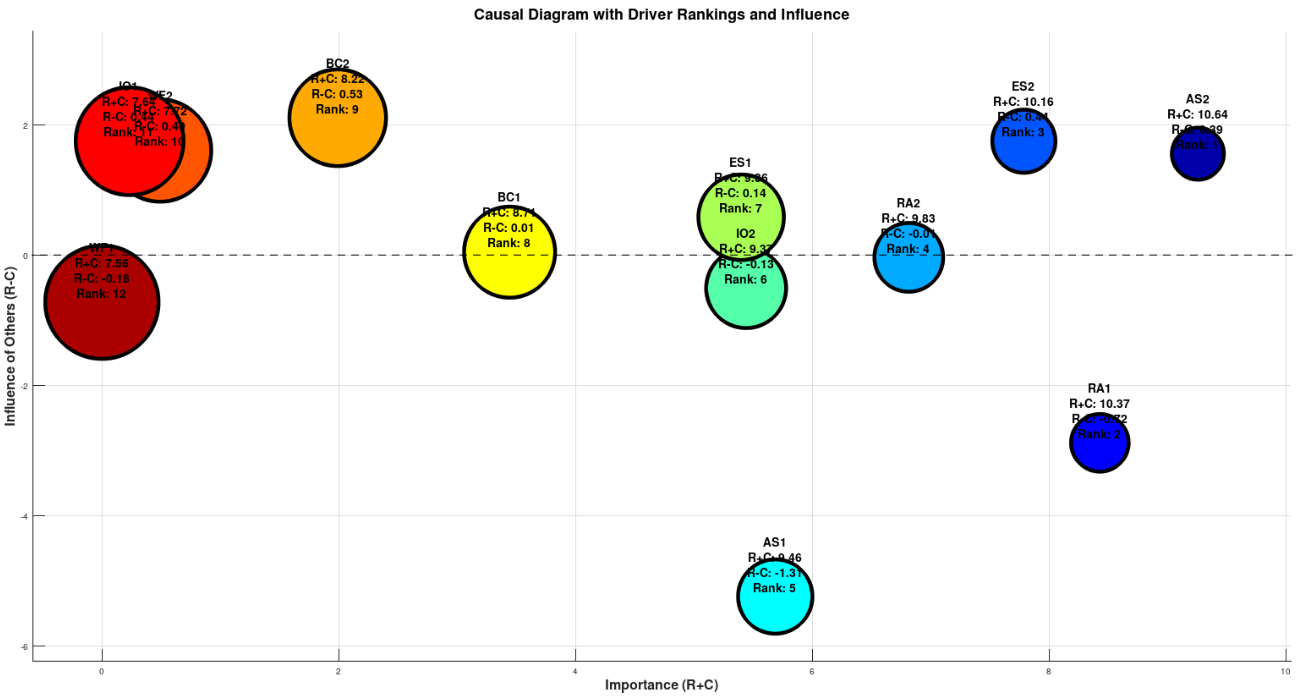

Figure 2. Causal diagram of the main drivers

On the other hand, the drivers located below the X-axis are considered effect drivers. These drivers have a negative influence value (R-C), indicating that they are more influenced by other factors than by their own ability to impact the system. In other words, these factors are not as significant in terms of causing changes in other elements of the model, but rather are the result of the influence of other drivers.

4. DISCUSSION

The results obtained in this study highlight the importance of each driver and factor within the sustainable agri-food system, as well as how they interrelate and influence decision-making in intervention strategies. By analyzing the driver weights obtained through the AHP method, it is observed that the driver "AS" holds the highest weight (0.314), emphasizing its central relevance within the model. This finding aligns with previous studies that stress the need to adapt and evolve agricultural systems to ensure long-term sustainability, highlighting the importance of innovation in agricultural practices to address challenges such as climate change and food security [1, 2]. On the other hand, "WF" ranks second with a weight of 0.231, underscoring the significance of efficient water management in the agri-food sector, in line with growing global concerns about water scarcity and its impact on agricultural sustainability [61].

The "RA" driver ranks third with a weight of 0.115. This result reflects the growing interest in the ability of the agri-food system to adapt and recover from negative impacts, such as climate change or economic crises, which is consistent with proposals from various studies emphasizing the importance of resilience for sustainability [62]. Fourth and fifth places are occupied by "BC" and "ES" with weights of 0.093 and 0.075, respectively. These drivers are crucial for promoting integration and coordination within AFSCs, which, according to authors like Fusto et al. [63], facilitates process optimization and improves efficiency in agri-food production systems. Environmental sustainability also stands out as a key factor for the sustainability of the chain, particularly regarding the preservation of natural resources and the reduction of negative environmental impacts [64].

Regarding the "IOT" driver, which occupies the last position with a weight of 0.034, this result reflects the still emerging role of digital technologies in the agri-food sector. Although the Internet of Things holds great potential to enhance agricultural management efficiency and product traceability [65], its impact is smaller compared to other more traditional drivers, such as water management and system resilience.

The consistency of the evaluation was validated by calculating the CR, with a value of 0.094, which is below the threshold of 0.1, ensuring that the results obtained are reliable and do not present significant contradictions in the driver weights.

On the other hand, the importance and influence matrix constructed using the DEMATEL method reinforces the hierarchy of the drivers within the model. The AS2 driver, with a value of 10.646, emerges as the most important factor, indicating that improving operations and coordination within the agri-food chain is crucial to optimizing system performance. This finding is supported by studies that emphasize the need for a more integrated and coordinated approach to managing AFSCs to improve efficiency and sustainability [63]. In second place is RA1, highlighting the relevance of having solid regulatory frameworks and inter-institutional agreements to support the transition to more sustainable agri-food systems. This point aligns with literature that underscores the need for public policies that incentivize sustainable and resilient practices within the agri-food sector [1, 66].

As for the drivers with lesser relevance, such as WF1, which ranks last with a value of 7.559, its low impact may reflect the growing importance of other factors more directly related to operational efficiency and sustainability in terms of production and distribution, while water management, although essential, does not appear to be a decisive factor in the overall model analyzed.

The analysis of the influence of the factors on the system, represented in the causal diagram, shows how certain drivers act as causal controllers, while others are more susceptible to external influences. This differentiation is essential for understanding the dynamics of interaction between the various elements of the agri-food system and identifying those factors with the greatest capacity to bring about structural transformations. In particular, the most relevant drivers, such as AS2, have a significant impact on other key components of the model, emphasizing their strategic role in the sustainability and resilience of AFSCs.

This study rigorously answers the research question posed by identifying and prioritizing the key drivers and factors in the sustainability of AFSCs. Through a SLR and the use of robust analytical methodologies such as AHP and DEMATEL, an integrated methodological framework is established to evaluate the relevance and impact of these factors. The findings indicate that drivers like AS and WF are determinants, underscoring the need to incorporate environmental criteria and climate change adaptation into strategic decision-making. Moreover, the prioritization of drivers such as AS2 and RA1 highlights the importance of strengthening organizational capacities and ensuring effective policy alignment to promote a systemic approach to sustainability within AFSCs.

The results of this study provide a clear view of the most influential factors in agri-food sustainability and offer a solid foundation for designing intervention strategies that prioritize the key drivers. The findings also highlight the importance of consistent evaluation and the need to apply robust methodological approaches like AHP and DEMATEL to understand the complexity of agri-food systems and their transition to more sustainable and resilient practices.

Furthermore, the main contribution of this study lies in the application of advanced analytical tools to prioritize these drivers and factors, providing a quantitative basis for strategic decision-making in the context of agri-food sustainability. This approach not only answers the research question posed but also contributes to the advancement of sustainability science in AFSCs, offering a replicable model for other supply chains.

Regarding future lines of research, it would be relevant to explore the practical implementation of the proposed models in specific contexts, analyzing their applicability and effectiveness in different regions and types of AFSCs. It is also recommended to delve into the analysis of the interaction between drivers through longitudinal studies that allow observing their evolution and the effects of policies and strategic decisions over the long term. Additionally, it would be valuable to incorporate socio-economic and cultural variables into the analysis of drivers, as these factors could significantly influence the sustainability and resilience of AFSCs in diverse contexts.

This study presents some limitations that should be considered in future research. Firstly, the SLR conducted was limited to English-language articles published between 2020 and 2024, which may have excluded important previous studies or significant contributions from non-English literature. This restriction may have reduced the breadth of the theoretical framework used, so the inclusion of more diverse sources and older literature could enrich the analysis and provide a more comprehensive view of the drivers and controllers of sustainability and resilience in AFSCs.

Another limitation of the study is its primarily theoretical approach, based on the hybrid AHP-DEMATEL model for prioritizing drivers. While this model provides a robust analytical framework, its applicability in real-world scenarios has not yet been empirically validated. Therefore, it is essential for future research to validate these models in practical contexts, assessing their effectiveness in different regions and types of AFSCs. This validation will provide evidence of the model's utility in specific situations, enhancing its value in strategic decision-making within AFSCs.

Despite these limitations, the significance of the research topic lies in the growing importance of sustainability and resilience in AFSCs, particularly in the current context of climate change, economic crises, and demand fluctuations. The proposed model not only contributes to prioritizing key drivers of sustainability but also offers a quantitative tool for strategic decision-making, making it a replicable model for other supply chains. Therefore, this research represents a significant advancement in the field of agri-food sustainability, providing a solid foundation for future research and practical applications.

5. CONCLUSIONS

AFSCs face significant challenges in terms of resilience and sustainability. In this context, the present study aimed to identify and prioritize key drivers and enablers that promote the sustainability of AFSCs. To achieve this, a SLR was conducted, and a hybrid methodology combining the AHP and the DEMATEL method was applied.

The results obtained provided answers to the research questions posed. First, it was identified that the main drivers of sustainability in AFSCs are the evaluation of AS, WF, and

RA. These elements play a crucial role in shaping sustainable strategies within the supply chain. Second, the prioritization of enablers through DEMATEL revealed that the AS2, RA1, and AS2 are the key factors that can be applied to strengthen the sustainability of AFSCs.

From these findings, it is concluded that integrating these drivers and enablers allows AFSCs to be transformed into sustainable systems. The application of an industrial symbiosis approach within a CE facilitates the transition from a linear model to a closed system, where the various links in the chain are efficiently interconnected, minimizing waste and optimizing resources.

In practical terms, the results of this research provide a solid foundation for decision-making in AFSC management, enabling stakeholders to develop strategies aimed at sustainability. The AHP-DEMATEL hybrid methodology proved to be an effective tool for evaluating interrelationships and prioritizing key elements within the supply chain, contributing to the formulation of more effective policies and practices in the agri-food sector. Future research could explore the implementation of these findings in specific contexts, considering additional variables such as the social and economic impact of sustainability in AFSCs.

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