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Prioritizing Vulnerability Factors of Global Food Supply Chains by Fermatean Fuzzy Analytical Hierarchy Process

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Abstract. In response to heightened competition arising from globalization, companies are crafting strategies to sustain their operations. However, these strategies also introduce risks that require meticulous management. The onset of the COVID-19 pandemic has exacerbated disruptions in supply chains, including the vulnerable food supply chain (FCS), strained further by escalating food prices and resource depletion in recent times. Within this context, the vulnerability of global FSCs has escalated significantly due to government-imposed lockdowns during the pandemic. This study aims to comprehensively investigate the multifaceted disruptions in global FSCs caused by the COVID-19 pandemic. By delving deep into the complexities of these disruptions, it seeks to uncover the key factors contributing to the vulnerability of supply chains. Employing a blend of literature review and expert opinions, the study identifies and prioritizes factors using the Fermatean Fuzzy Analytical Hierarchy Process (FF-AHP). A two-level criteria framework consisting of three main criteria and eleven sub-criteria has been developed, taking into account expert recommendations and previous studies. According to the results obtained, it has been revealed that the Managerial factors within the main criteria are the most significant factors in the fragility of the FSC. Among these factors, it has been observed that Technology, Corporation, and Inventory Management are the leading criteria causing to the vulnerability of the FSC. This is the first study to investigate the vulnerabilities of FSC using fuzzy logic. The research underscores the imperative of comprehensive risk management strategies that encompass all stakeholders within the supply chain, particularly during unanticipated crises like pandemics.

Keywords: Food supply chains, Vulnerability analysis, Analytical hierarchy process, Fermatean fuzzy numbers

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1. Introduction

Many natural resources are required for the proper functioning of the food supply chain (FSC). No industry other than the energy industry will face as much demand as the food industry due to the growing world population. The current global FSC supports nearly 7 billion people worldwide. As the world's population continues to grow, the management of the FSC will remain a focus for consumers and the media. It is an area that will continue to challenge managers and policy makers for years to come [57]. The critical issue of the FSC has faced significant challenges due to the impact of the COVID-19 outbreak. The pervasive nature of the COVID-19 has affected all industries. While some sectors have thrived, others have borne the brunt of the epidemic's negative impact. Unfortunately, the FSC falls into the latter category and has experienced notable disruptions as a result of the pandemic. These disruptions have highlighted the inadequacy of existing methods to comprehensively analyst breakdowns within the chain. The supply chain encompasses all processes from raw material procurement to the delivery of the final product to the customer. In order to reduce the overall fragility in the FSC, it is necessary to identify and manage every unpredictable risk that may arise at the beginning and end of the chain. This highlights the importance of strategies in the supply chain.

Any disruption in the supply chain results in the failure to deliver food products to consumers on time, leading to financial losses and a decline in product quality. The FSC is highly susceptible to factors such as epidemic diseases, natural disasters, war, and terrorism. This study aims to prioritize factors that could potentially harm the food chain in strategic decision-making and to understand the levels of importance, thus mitigating the impact of disruptions, especially those caused by COVID-19. This study will identify factors related to the sensitivity of the FSC, emphasizing the importance of the research. We use the Fermatean Fuzzy Analytical Hierarchy Process (FF-AHP) approach to identify and analyse weaknesses in the FSC. Despite the widespread use of AHP in the literature, the application of the Fermatean Fuzzy extension remains relatively unexplored, highlighting the need for innovative approaches to understanding and mitigating the impact of disruptions in this crucial sector. Fermatean fuzzy sets (FFSs) are an extension of Pythagorean fuzzy sets (PFSs). It is also an enhanced version of intuitionistic fuzzy sets (IFSs) according to fuzzy set theory (FST) [9]. Due to their more flexibility and the contain of more information compared to other fuzzy sets, FFSs provide realistic and precise results in modeling real-life problems. FFSs effectively address problems containing uncertain and incomplete information. This makes FFSs more advantageous compared to other fuzzy set extensions.

In the literature, AHP and other fuzzy set extensions of AHP are often utilized for various objectives. Bevilacqua and Braglia [12] employed AHP to ascertain the best maintenance plan for a well-known oil refinery in Italy. Kaya and Kahraman [34] used an integrated fuzzy VIKOR-AHP technique that takes fuzziness into account to decide which renewable energy option would be best for Istanbul. Ilbahar et al. [28] recognized the improved ability of intuitionistic fuzzy sets (IFS) to handle uncertainty and therefore proposed an innovative integrated approach, which consists of Fine

Kinney, Pythagorean Fuzzy AHP (PF-AHP), and a Fuzzy Inference System (FIS) for risk assessment in the occupational health and safety field. This approach is specifically designed for risk assessment in occupational safety and health. Spherical Fuzzy AHP (SF-AHP) was created by Kutlu Gündoğdu and Kahraman [45] and utilized in the renewable energy sector. Abdel-Basset et al. [1] used both SWOT analysis and AHP in a neutrosophic environment to overcome this disadvantage, as SWOT analysis that examines strength, weakness, opportunities, thread does not measure factors and does not rank available alternatives. Ayyildiz and Taskin Gumus [11] used voting AHP methodology to evaluate the risks on the distance learning ergonomics. Kavus et al. [33] evaluated the service quality factors for airline sector via neutrosophic AHP. Yildiz et al. [67] used type-2 fuzzy AHP approach to rank the expectations from water treatment plants in order of importance. These studies highlight the versatility and adaptability of AHP and its fuzzy extensions in different domains. However, upon reviewing the literature, it is noticeable that there are a limited number of studies conducted with FF-AHP, and the topics studied are mostly outside the realm of FCS.

Ayub et. al. [9] evaluated the sustainable waste valuation processes using the AHP method integrated with the CODAS method in a fermatean fuzz environment. Suvitha et. al. [62] determined the most suitable plastic waste collection system using the AHP-CODAS methods with the assistance of Fermatean probabilistic hesitant fuzzy sets. Kirisci [36] addressed the risks of autonomous vehicle driving systems by using fermatean fuzzy-based AHP, TOPSIS and MABAC methods. Hoang et. al. [27] evaluated the key environmental, social, and governance (ESG) criteria affecting investment using SF-AHP and SF-WASPAS methods and compared the results with the Fermatean Fuzzy-WASPAS method. Kirisci [37] examined the risks involved in decentralized finance using the FF-AHP approach. Manirathinam et. al. [50] addressed the selection of sustainable renewable energy systems for self-sufficient households with the integrated Fermatean neutrosophic fuzzy stratified AHP-MARCOS approach. Karuppiah et. al. [31] evaluated the challenges of human-robot collaboration in an industrial environment using integrated AHP-DEMATEL methods with fermatean fuzzy sets (FFSs). Bouraima et. al. [13] utilized interval-valued Fermatean fuzzy-based integrated AHP and TOPSIS to evaluate the causes of accidents occurring at construction sites. Nguyen et. al. [56] proposed an integrated method combining Data Envelopment Analysis (DEA) under a spherical fuzzy environment, AHP and WASPAS to evaluate the ESG performance of wire and cable companies in Vietnam. Karuppiah and Sankaranarayanan [32] used integrated Fermatean fuzzy-based DEMATEL, AHP, and TOPSIS methods to evaluate e-waste reduction strategies. Fahmi [22] addressed the FF-AHP-TOPSIS method for the selection of particle swarm optimization. To assess the quality of online teaching utilizing FFSs, introduced a unique approach based Zeng et al. [71] on the AHP and Dombi-Weighted Partitioned Muirhead Mean (PMM). Camci et. al. applied the FF-AHP method to a supplier selection problem in the transition to Industry 4.0. Using FF-AHP method, Alkan and Kahraman [7] identified the criteria that enterprises should take into account when digitalizing the supply chain. Using the criteria, they then decided which digitalization plan is the best.

The novelty of the paper lies in the exploration of vulnerability factors within FSCs using the FF-AHP method, a novel approach that has been little addressed in the existing literature. While various methodologies have been used to investigate the vulnerability of FSCs, the FF-AHP represents a distinctive and underexplored avenue. Its use in this study offers a fresh perspective and provides unique insights into the prioritization of vulnerability factors in the FSC.

The following sections of this study are structured to provide a structured understanding of this innovative methodology and its implications. The organization of the remainder of the study is detailed below: The procedures of the FF-AHP are introduced in Section 2. The prioritization vulnerability factors of FSCs are briefly explained, and the proposed methodology is applied in FSCs in Sect. 3. Practical implications of this study are presented in Sect. 4. Lastly, Sect. 5 presents conclusions and recommendations for future studies.

2. The Proposed Methodology

In the literature, the AHP approach is frequently employed to obtain criteria weights. The traditional AHP method, however, is inappropriate in uncertain situations. For this reason, the AHP approach is integrated with various fuzzy sets to provide effective outcomes. The FF-AHP is an extension to AHP designed to address challenging decision-making problems under fermatean fuzzy environments. Fuzzy set theory is introduced by Zadeh [69]. The introduction of different fuzzy set extensions is then made to address fuzziness. Fuzzy sets are a useful technique for resolving informational ambiguity. Intuitionistic Fuzzy Sets (IFSs) is presented by Atanassov [8] which have both membership and non-membership degrees. These functions' both degrees for membership and non-membership must be equal or lower than 1. Pythagorean Fuzzy Sets (PFSs), that are based on IFSs, were developed by Yager [66].

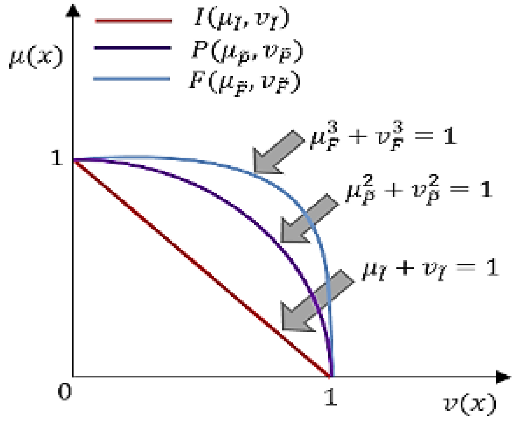

Figure 1. A comparison of the space of membership grades of IFSs, PFSs and FFSs [9]

Sum of squares of membership and non-memberships, nevertheless, is limited to 1. In some situations, intuitionistic membership grade (IMG) ($\mu_{\tilde{I}} + v_{\tilde{I}} \leq 1$) and Pythagorean membership grade (PMG) ($\mu_{\tilde{P}}^2 + v_{\tilde{P}}^2 \leq 1$) fail to comply with this constraint [9]. To eliminate this limitation to deal with ambiguous, incomplete, and imprecise information, Senapati and Yager [59] presented FFSs as extension of IFSs and PFSs. In Fig. 1, it is observed that the space of Fermatean membership grade (FMG) is larger than the space of PMG and the IMG. The more flexible and easily applicable of FFSs, this gives FFSs an edge over IFSs and PFSs in modeling uncertainty in real-life problems.

Due to their adaptability, FFSs are helpful for resolving MCDM problems [7]. Below, the fundamental definitions of FFSs are introduced ([7]; [59]; [39]).

Definition 1. A fermatean fuzzy number (FFN) $\tilde{E}$ in universe of discourse X is defined as:

$$\tilde{E} = \{\langle x, \mu_{\tilde{E}}(x), v_{\tilde{E}}(x)\rangle \mid x \in X\} \tag{1}$$

$\mu_{\tilde{E}} : X \to [0,1]$ and $v_{\tilde{E}} : X \to [0,1]$ ddefine to degree for membership and non-membership, for $\forall x \in X$ where;

$$0 \leq (\mu_{\tilde{E}}(x))^3 + (v_{\tilde{E}}(x))^3 \leq 1 \tag{2}$$

Definition 2. An interval valued fermatean fuzzy number (IVFFN) $\tilde{F}$ is expressed:

$$\tilde{F} = \{\langle x, \mu_{\tilde{F}}(x), v_{\tilde{F}}(x)\rangle \mid x \in X\} \tag{3}$$

For every $\forall x \in X$, $\mu_{\tilde{F}}(x)$ and $v_{\tilde{F}}(x)$ re close intervals and their lower and upper bounds are denoted by $\mu_{\tilde{F}}^L(x)$, $\mu_{\tilde{F}}^U(x)$,$v_{\tilde{F}}^L(x)$ and $v_{\tilde{F}}^U(x)$ respectively. Therefore, $\tilde{F}$ is defined:

$$\mu_{\tilde{F}}(x) = \left[\mu_{\tilde{F}}^L(x), \mu_{\tilde{F}}^U(x)\right] \subseteq [0,1] \tag{4}$$

$$v_{\tilde{F}}(x) = \left[v_{\tilde{F}}^L(x), v_{\tilde{F}}^U(x)\right] \subseteq [0,1] \tag{5}$$

where $0 \leq (\mu_{\tilde{E}}(x))^3 + (v_{\tilde{E}}(x))^3 \leq 1$. For every $\forall x \in X$, the degree of hesitancy $\pi_{\tilde{F}}(x)$ to $\tilde{F}$ as:

$$\pi_F(x) = \left[\pi_{\tilde{F}}^L(x), \pi_{\tilde{F}}^U(x)\right] = \left[\sqrt[3]{1 - \left(\mu_{\tilde{F}}^U(x)\right)^3 - \left(v_{\tilde{F}}^U(x)\right)^3}, \sqrt[3]{1 - \left(\mu_{\tilde{F}}^L(x)\right)^3 - \left(v_{\tilde{F}}^L(x)\right)^3}\right] \tag{6}$$

Definition 3. Let $\tilde{F} = \left(\left[\mu_{\tilde{F}}^L, \mu_{\tilde{F}}^U\right], \left[v_{\tilde{F}}^L, v_{\tilde{F}}^U\right]\right)$, $\tilde{F}_1 = \left(\left[\mu_{\tilde{F}_1}^L, \mu_{\tilde{F}_1}^U\right], \left[v_{\tilde{F}_1}^L, v_{F_1}^U\right]\right)$ and $\tilde{F}_2 = \left(\left[\mu_{\tilde{F}_2}^L, \mu_{\tilde{F}_2}^U\right], \left[v_{\tilde{F}_2}^L, v_{F_2}^U\right]\right)$ be three IVFFNs and λ is positive scalar. Then some basic mathematical operations are:

$$\lambda\tilde{F} = \left(\left[\sqrt[3]{1-\left(1-\left(\mu_{\tilde{F}}^{L}\right)^{3}\right)^{\lambda}}, \sqrt[3]{1-\left(1-\left(\mu_{\tilde{F}}^{U}\right)^{3}\right)^{\lambda}}\right], \left[\left(v_{\tilde{F}}^{L}\right)^{\lambda}, \left(v_{\tilde{F}}^{U}\right)^{\lambda}\right]\right) \tag{7}$$

$$\tilde{F}^{\lambda} = \left(\left[\left(\mu_{\tilde{F}}^{L}\right)^{\lambda}, \left(\mu_{\tilde{F}}^{U}\right)^{\lambda}\right], \left[\sqrt[3]{1-\left(1-\left(v_{\tilde{F}}^{L}\right)^{3}\right)^{\lambda}}, \sqrt[3]{1-\left(1-\left(v_{\tilde{F}}^{U}\right)^{3}\right)^{\lambda}}\right]\right) \tag{8}$$

$$\tilde{F}_1 \oplus \tilde{F}_2 = \left(\left[\begin{array}{c}\sqrt[3]{\left(\mu_{\tilde{F}_1}^{L}\right)^{3}+\left(\mu_{\tilde{F}_2}^{L}\right)^{3}-\left(\mu_{\tilde{F}_1}^{L}\right)^{3}\left(\mu_{\tilde{F}_2}^{L}\right)^{3}} \\ \sqrt[3]{\left(\mu_{\tilde{F}_1}^{U}\right)^{3}+\left(\mu_{\tilde{F}_2}^{U}\right)^{3}-\left(\mu_{\tilde{F}_1}^{U}\right)^{3}\left(\mu_{\tilde{F}_2}^{U}\right)^{3}}\end{array}\right], \left[v_{\tilde{F}_1}^{L}v_{\tilde{F}_2}^{L}, v_{\tilde{F}_1}^{U}v_{\tilde{F}_2}^{U}\right]\right) \tag{9}$$

$$\tilde{F}_1 \otimes \tilde{F}_2 = \left(\left[\mu_{\tilde{F}_1}^{L}\mu_{\tilde{F}_2}^{L}, \mu_{\tilde{F}_1}^{U}\mu_{\tilde{F}_2}^{U}\right], \left[\begin{array}{c}\sqrt[3]{\left(v_{\tilde{F}_1}^{L}\right)^{3}+\left(v_{\tilde{F}_2}^{L}\right)^{3}-\left(v_{\tilde{F}_1}^{L}\right)^{3}\left(v_{\tilde{F}_2}^{L}\right)^{3}} \\ \sqrt[3]{\left(v_{\tilde{F}_1}^{U}\right)^{3}+\left(v_{\tilde{F}_2}^{U}\right)^{3}-\left(v_{\tilde{F}_1}^{U}\right)^{3}\left(v_{\tilde{F}_2}^{U}\right)^{3}}\end{array}\right]\right) \tag{10}$$

Definition 4. Let $\tilde{F} = \left(\left[\mu_{\tilde{F}}^{L}, \mu_{\tilde{F}}^{U}\right], \left[v_{\tilde{F}}^{L}, v_{\tilde{F}}^{U}\right]\right)$ be an IVFFN. The score function $\mathrm{S}(\tilde{F})$ is defined.

$$\mathrm{S}(\tilde{F}) = \frac{\left(\mu_{\tilde{F}}^{L}\right)^{3}+\left(\mu_{\tilde{F}}^{U}\right)^{3}-\left(v_{\tilde{F}}^{L}\right)^{3}-\left(v_{\tilde{F}}^{U}\right)^{3}}{2} \tag{11}$$

Below are the steps for applying the FF-AHP approach [7]:

Step 1. The criteria are identified to create the hierarchical structure.

Step 2. The linguistic terms described in Table 1 are employed to generate the FF pairwise comparison (PC) matrix.

Table 1. Linguistic terms

Linguistic Terms	**IVFFNs**			
	μ_L	μ_U	v_L	v_U
CH-Certainly High Important	0.95	1	0	0
VH-Very High Important	0.8	0.9	0.1	0.2
H-High Important	0.7	0.8	0.2	0.3
SH-Slightly High Important	0.6	0.65	0.35	0.4
E-Equally Important	0.5	0.5	0.5	0.5
SL-Slightly Less Important	0.35	0.4	0.6	0.65
L-Low Important	0.2	0.3	0.7	0.8
VL-Very Low Important	0.1	0.2	0.8	0.9
CL-Certainly Low Important	0	0	0.95	1

Step 3. The consistency of PC matrix is investigated. Saaty's traditional consistency calculation process is employed to find the consistency ratio (CR).

Step 4. Eqs. (12) and (13) are used to determine the differences matrix.

$$d_{ij}^{L} = \left(\mu_{ij}^{L}\right)^{3} - \left(v_{ij}^{U}\right)^{3} \tag{12}$$

$$d_{ij}^{U} = \left(\mu_{ij}^{U}\right)^{3} - \left(v_{ij}^{L}\right)^{3} \tag{13}$$

Step 5. Using Eqs. (14) and (15), the interval multiplicative matrix is derived.

$$s_{ij}^{L} = \sqrt[3]{1000^{d_{ij}^{L}}} \tag{14}$$

$$s_{ij}^{U} = \sqrt[3]{1000^{d_{ij}^{U}}} \tag{15}$$

Step 6. The expert evaluations' indeterminacy values are determined.

$$t_{ij} = 1 - \left(\mu_{ij_U}^{3} - \mu_{ij_L}^{3}\right) - \left(v_{ij_U}^{3} - v_{ij_L}^{3}\right) \tag{16}$$

Step 7. To get the unnormalized weight matrix, the indeterminacy values are multiplied by the interval multiplicative matrix.

$$r_{ij} = \left(\frac{s_{ij}^{L} + s_{ij}^{U}}{2}\right) t_{ij} \tag{17}$$

Step 8. The normalized priority weights are determined in the end.

$$w_i = \frac{\sum_{j=1}^{m} r_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{m} r_{ij}} \tag{18}$$

3. Application

An evaluation framework is established to prioritize the vulnerability factors of FSCs in this study. As a result of the recommendations of the expert team provided in Table 3 and an analysis of previous studies ([10]; [26]; [17]; [19]; [29]; [60]), a two-level criteria framework is constructed to prioritize the factors related to the vulnerability of the FSC. The first level is comprised of three key criteria: Managerial, Agility, and Green. The selection process involved careful consideration of various dimensions, including managerial, agility, and environmental factors, among others. Criteria were chosen based on their relevance, significance, and applicability to the context of FSCs. Additionally, we paid close attention to ensuring that the chosen criteria aligned with the scope and objectives of our study. The criteria set and its sources are shown in Table 2.

Table 2. Evaluation criteria

Main Criteria	Sub Criteria	Resources
Managerial	**C1**. Corporation	[10]
	C2. Human Resource Management	[52],[70]
	C3. Inventory Management	[4],[65]
	C4. Technology	[2],[39]
Agility	**C5**. Responsiveness	[10],[11]
	C6. Automation	[40],[53]
	C7. Flexibility	[10],[11]
	C8. Reliability	[10],[11]
Green	**C9**. Health	[16],[21]
	C10. Environmental	[20],[41]
	C11. Social	Expert view

The weight of each criterion was determined by taking the opinions of the expert team ensemble, consisting of E-1 through E-5. The detailed information on each expert's experience, education, and job title is provided in Table 3.

Table 3. Information about experts

	Experience	Education Level	Job Title	Field of Expertise
E-1	15 years	MS in Transportation and Logistics Management	Supply Chain Specialist	Planning and System Specialist
E-2	6 years	PhD in Mechanical Engineering	Assist. Prof. Dr.	Production process
E-3	4 years	PhD in Supply Chain Management	Industrial Engineer	Inventory Management
E-4	8 years	MS in Engineering Management	Production Planning Manager	Material Requirement Plan
E-5	8 years	PhD in Industrial Engineering	Assoc. Prof. Dr.	Enterprise Resource Planning

The composition of the expert team from different areas of expertise significantly strengthens the reliability and applicability of the methodology. As mentioned above, experts are engaged to calculate the weighting of each criterion. They are given a questionnaire to rate the criteria at each level. First, the experts construct a PC matrix for the main criteria via the linguistic terms in Table 1. Table 4 shows the resulting matrix, illustrating the experts' assessments of the main criteria.

Firstly, matrix is tested for consistency and determined as consistent with CR value 0.068. The experts' opinions are then aggregated. Difference matrix between lower and upper values are generated based on Eqs. (12) and (13). The interval generative matrix is generated to Eqs. (14) and (15). The uncertainty value for each criteria is calculated. Unnormalized weights are calculated based via Eq. (17). Finally, weights are normalized to Eq. (18) and the criteria weights are determined. The weights of main criteria, Managerial, Agility, and Green, are obtained as 0.588, 0.250 and 0.162. The results of first level emphasize that the Managerial criteria is the most critical criterion. Following in critical importance is the Agility criterion.

Table 4. PC matrix for main criteria

	Managerial	**Agility**	**Green**
Managerial	E	H	VH
Agility	L	E	SH
Green	VL	SL	E

The inner levels of criteria are then evaluated by the same experts. PC matrices for the sub criteria are created based on expert judgment. In Table 5, the matrices for the PC of the sub-criteria are depicted. As in the main criteria matrix, the matrices are checked for consistency and each of them is determined as consistent. The CR value for each matrix is shown in Table 5.

Table 5. PC matrices for the sub-criteria

Managerial CR=0.073					**Agility CR=0.042**					**Green CR=0.04**			
	C1.	**C2.**	**C3.**	**C4.**		**C5.**	**C6.**	**C7.**	**C8.**		**C9.**	**C10.**	**C11.**
C1.	E	H	SH	E	**C5.**	E	SH	H	H	**C9.**	E	SL	SH
C2.	L	E	SL	L	**C6.**	SL	E	E	SH	**C10.**	SH	E	H
C3.	SL	SM	E	L	**C7.**	L	E	E	E	**C11.**	SL	L	E
C4.	E	H	H	E	**C8.**	L	SL	E	E				

According to Table 5, the consistency ratio is CR <= 0.1 for each sub-criteria matrix. This indicates that expert opinions yield consistent results. Then, the FF-AHP processes are once again applied to obtain the sub criteria weights. To calculate the final weights for sub-criteria, the corresponding main criterion weight is multiplied with those of the sub-criteria. Table 6 shows the criteria weights. The most significant criteria are all related to Managerial. This outcome is anticipated since Technology is the main key criteria. Corporation and Inventory Management come in 2nd and 3rd, with final of 0.188 and 0.112.

Table 6. Criteria weights

	Local Weight	Final Weight
C1. Corporation	0.320	0.188
C2. Human Resource Management	0.127	0.075
C3. Inventory Management	0.191	0.112
C4. Technology	0.362	0.213
C5. Responsiveness	0.398	0.100
C6. Automation	0.236	0.059
C7. Flexibility	0.195	0.049
C8. Reliability	0.171	0.043
C9. Health	0.317	0.051
C10. Environmental	0.483	0.078
C11. Social	0.200	0.032

4. Policy Implications

The FF-AHP is applied to prioritize the vulnerability factors of FSCs. The main criteria used were Managerial, Agility, and Green, while the sub-criteria included Corporation, Human Resource Management, Inventory Management, Technology, Responsiveness, Automation, Flexibility, Reliability, Health, Environmental, and Social. The results showed that the most important main criterion for vulnerabilities in the FSC was Managerial. The results have important policy implications for FSC management. The prioritization of managerial factors suggests that companies should focus on improving their technology, inventory management and human resource management practices to reduce supply chain vulnerabilities [65]. The Corporation includes the structure and management of the organization responsible for managing the FSC. Effective collaboration is essential to ensure open communication and coordination between all stakeholders in the supply chain [24]. Human Resource Management involves the recruitment, training and management of personnel involved in the FSC. A well-trained and motivated workforce is critical to the smooth functioning of the FSC [42]. Inventory management involves the management of stocks at different stages of the supply chain. Effective inventory management is important to ensure an adequate supply of food to meet demand while minimizing waste and spoilage [5]. Technology involves the use of advanced technologies to manage the FSC. Technology can help increase efficiency, reduce costs and improve the speed and accuracy of information flow [49].

The COVID-19 pandemic exposed vulnerabilities in global FSCs ([23]; [55]) and highlighted the critical importance of effective management practices to ensure a resilient and sustainable food supply [51]. During the pandemic, many FSCs were disrupted by various factors such as border closures, supply chain constraints and changes in consumer demand ([47]; [61]). Effective management practices such as inventory management, communication and collaboration among stakeholders, and the use of advanced technologies were critical to managing these disruptions and ensuring continuity of food supply [42]. Companies with strong management practices were better able to adapt and respond to changing market conditions and disruptions caused by the pandemic ([38]; [58]). In the post-COVID-19 era, effective management practices will be essential to ensure the long-term resilience and sustainability of the FSC. The pandemic has highlighted the need for more efficient and sustainable FSCs that are better equipped to deal with future disruptions [48]. To better manage risk and increase resilience, companies will need to focus on improving management practices such as inventory management, supply chain transparency and the use of advanced technologies. Effective management practices will also be critical in addressing the social and environmental challenges facing the FSC [54]. The pandemic has highlighted the importance of social sustainability and the need for companies to prioritize the health and safety of workers in the FSC [44]. Companies will need to adopt responsible and sustainable practices to address the environmental challenges facing the FSC, such as reducing food waste and greenhouse gas emissions. Overall, effective management practices will be critical to ensuring a resilient FSC during and beyond COVID-19. Businesses and policy makers will need to prioritize these practices to address the challenges facing the FSC and ensure a safe, secure and sustainable food supply for all [43].

Technology is the most important subcriterion of FSC vulnerability because of its critical role in enabling efficient and effective supply chain management. In today's digital age, technology has become an essential tool for managing complex supply chains [3], and its importance has become even more apparent in the wake of the COVID-19 pandemic [35]. The use of advanced technologies such as supply chain management software, real-time monitoring systems and automated warehousing systems can help improve supply chain visibility and coordination [64], which is essential to ensure the timely and efficient delivery of food products [6]. These technologies enable stakeholders to track the movement of products through the supply chain, identify problems or delays and take appropriate action in real time. Another critical aspect of technology is its role in enhancing the safety and security of the FSC ([18]; [68]). By utilizing blockchain technology, the FSC may become more transparent and traceable, which will facilitate the process of determining the origin of an issue or contamination in the supply chain [15]. This can help reduce the risk of foodborne illness and improve the safety and security of the FSC. Through the facilitation of more effective resource use and waste reduction, technology may also aid in mitigating the environmental impact of the FSC. The use of automated systems for inventory management and food processing can help reduce food waste [46], while the use of electric vehicles for transport can help reduce greenhouse gas emissions [25].

5. Conclusion

Supply chain managers were worried about the supply chain vulnerability before COVID-19, but these worries have now been complicated by the worldwide epidemic. Businesses and communities have moved beyond traditional modes of production and consumption, and there is a growing preference for quick-shipping platforms like ecommerce. As a result, companies are finding it difficult to meet demand using their standard supply networks. Due to the unexpected increase in demand for additional food goods and people's storage requirements, the inventories have run out since the pandemic spread. To meet these demands, FSCs started to use their stockpiles more quickly, but they quickly ran out. Due to the unexpected emergence and rapid disruption of regular life caused by life threatening illnesses like COVID-19, food supply networks have not had time to prepare for such a catastrophe. This demonstrated once more to all chain stakeholders the need to consistently be ready for the worst-case situation. The idea of supply chain vulnerability has to be integrated more deeply into supply chains so that they may be more robust in a market environment and, under ordinary situations, transport all stakeholders to a better place. Unquestionably, supply chain network structure is crucial for managing supply chain risks. Working with several suppliers, for instance, can lower the supply risk, and setting up manufacturing facilities with flexible capacity will provide a barrier against changes in demand, price, and currency rates. The notion of supply chain resilience describes how complex networks may remain connected, endure, and bounce back from interruptions and major catastrophes. Assuring the continuity of a company's activities in the face of uncertainties and interruptions is the main worry about the supply chain's vulnerability.

This study aims to prioritize factors causing vulnerability in the FSC in the event of a pandemic, terrorism, or natural disasters, in order to prevent disruptions in the supply chain. The identification of factors contributing to the vulnerability of the FSC is crucial. Therefore, a two-level criteria evaluation has established by analyzing the opinions of five experts in their respective fields and previous studies. The determination of the importance levels of criteria has carried out using the FF-AHP method. The FF-AHP method, being more flexible and containing more information compared to other fuzzy set extensions in the literature, facilitates experts in expressing their opinions more easily. The findings of the research suggest that managerial activities in the FSC are critically important. The importance of strategic decisions in food supply also emerges here. It has been concluded that criteria such as technology and inventory management play a critical role in the FCS. Proper management of the supply chain is crucial to prevent damage to all links of the chain in the face of potential risks.

Technology and corporation are the most important aspects associated to supply chain vulnerability, according to the results of the application developed for this study. In this situation, a technology infrastructure that includes all supply chain stakeholders will strengthen the chain's resilience. By utilizing blockchain in the supply chain, it is feasible to create a viable financial solution. With the blockchain, every step from the supplier to the client's customer is preserved in a digital environment, accurate and trustworthy information can be retrieved more readily, and the flexibility required in emergency situations is accomplished.

Due to the significance of the topic, supply chain durability and vulnerability should be thoroughly communicated to internal and external stakeholders (workers, managers, suppliers, consumers, society, etc.). A comprehensive strategy that encompasses more than just a few skilled workers and companies is needed to build

FSC resilience. The idea of FSC vulnerability presents a solution for current supply chains to first get rid of the issues before improving in order to guarantee company continuity. Businesses may strengthen their ability to compete in this way.

Although the study provides valuable contributions, it also has some limitations. The relationships between the criteria have not been addressed. Therefore, future studies could be directed in this direction. The effects of criteria can be examined on a real problem. Comparisons can be made with different methods in the literature, and the results can be analyzed accordingly.

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