Research Article

INTEGRATED FERMATEAN FUZZY SWARA-WASPAS METHODS FOR SUSTAINABLE SUPPLIER SELECTION

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ABSTRACT

In today's business landscape, sustainable supplier selection has gained strategic significance, not only due to ethical responsibilities but also as a key factor in enhancing competitive advantage and managing long-term risks. Stakeholders such as consumers, investors, and regulatory agencies increasingly expect companies to adopt sustainability principles throughout their supply chains. Consequently, integrating environmental, social, and governance (ESG) criteria alongside traditional economic indicators has become essential. This study focuses on a large-scale retail organization’s supplier evaluation process by incorporating sustainability-oriented decision-making criteria. Building on a comprehensive literature review, existing evaluation criteria were revised and expanded to include ESG dimensions, forming a holistic framework of 18 sub-criteria across four primary categories: economic, environmental, social, and governance. To determine the importance of these criteria, the Fermatean Fuzzy SWARA method was applied, and supplier alternatives were prioritized using the Fermatean Fuzzy WASPAS technique. The findings provide actionable insights for practitioners seeking to enhance sustainable procurement practices.

Keywords: Sustainable Supplier Selection, Fermatean Fuzzy Sets, SWARA, WASPAS.

SÜRDÜRÜLEBİLİR TEDARİKÇİ SEÇİMİ İÇİN BÜTÜNLEŞİK FERMATEAN BULANIK SWARA-WASPAS YÖNTEMLERİ

ÖZET

Günümüz iş dünyasında sürdürülebilir tedarikçi seçimi, yalnızca etik sorumluluklar nedeniyle değil, aynı zamanda rekabet avantajını artırmak ve uzun vadeli riskleri yönetmek açısından da stratejik bir önem kazanmıştır. Tüketiciler, yatırımcılar ve düzenleyici kurumlar gibi paydaşlar, şirketlerin tedarik zincirlerinin tamamında sürdürülebilirlik ilkelerini benimsemelerini giderek daha fazla beklemektedir. Bu nedenle, geleneksel ekonomik göstergelere ek olarak çevresel, sosyal ve yönetişim (ÇSY) kriterlerinin entegre edilmesi artık bir gereklilik hâline gelmiştir. Bu çalışma, büyük ölçekli bir perakende kuruluşunun tedarikçi değerlendirme sürecine odaklanmakta ve sürdürülebilirlik odaklı karar verme kriterlerini içermektedir. Kapsamlı bir literatür taramasına dayanarak mevcut değerlendirme kriterleri gözden geçirilmiş ve ÇSY boyutlarını içerecek şekilde genişletilerek ekonomik, çevresel, sosyal ve yönetişim olmak üzere dört ana kategori altında 18 alt kriterden oluşan bütüncül bir çerçeve oluşturulmuştur. Bu kriterlerin önem düzeylerini belirlemek için Fermatean Bulanık SWARA yöntemi uygulanmış, tedarikçi alternatifleri ise Fermatean Bulanık WASPAS tekniğiyle önceliklendirilmiştir. Elde edilen bulgular, sürdürülebilir tedarik uygulamalarını geliştirmek isteyen uygulayıcılara yönelik uygulanabilir içgörüler sunmaktadır.

Anahtar Kelimeler: Sürdürülebilir Tedarikçi Seçimi, Fermatean Bulanık Kümeler, SWARA, WASPAS.

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1. INTRODUCTION

In the face of growing environmental degradation, resource scarcity, and social inequality, sustainability has become a critical consideration across all domains of business operations. Supply Chain Management (SCM), as a strategic function that links upstream suppliers to downstream consumers, plays a pivotal role in an organization's efforts to achieve environmental and social goals. Traditional supply chain models have prioritized efficiency, cost minimization, and speed; however, these goals are no longer sufficient in isolation. Organizations are increasingly expected to adopt a triple bottom line approach—addressing not only economic outcomes but also environmental and social performance.

Sustainable Supply Chain Management (SSCM) has thus emerged as a transformative extension of conventional SCM, requiring businesses to engage in ethical sourcing, waste minimization, energy efficiency, and stakeholder inclusiveness throughout the supply chain. The supplier selection process, as the initial and arguably most influential step in the supply chain, is central to these efforts. Selecting suppliers that align with sustainability values can enhance corporate reputation, ensure regulatory compliance, mitigate supply risks, and contribute to long-term competitiveness.

However, sustainable supplier selection is inherently complex due to the need to evaluate diverse and sometimes conflicting criteria, such as cost, environmental compliance, labor practices, and governance standards. These evaluations often involve qualitative judgments and uncertain or imprecise data. As a result, decision-makers increasingly turn to Multi-Criteria Decision-Making (MCDM) techniques that are capable of handling such complexity.

The literature reflects a growing interest in combining traditional MCDM methods with fuzzy logic approaches to better accommodate uncertainty and subjectivity in sustainability assessments. Techniques such as AHP, TOPSIS, and ANP have been widely used, and recent studies have proposed hybrid models integrating fuzzy sets with these methods to improve decision quality. In particular, Fermatean Fuzzy Sets (FFS) have gained attention for their ability to represent uncertainty more effectively than earlier fuzzy models.

This study contributes to this evolving body of knowledge by proposing an integrated MCDM framework using Fermatean Fuzzy SWARA and Fermatean Fuzzy WASPAS methods to support sustainable supplier selection. The SWARA method is used to determine the relative importance of each criterion based on expert input, while the WASPAS method is employed to rank supplier alternatives based on aggregated performance scores. The model is applied in the context of a major retail company, offering practical insights into how organizations can operationalize sustainability in procurement decisions.

The remainder of this paper is organized as follows. Section 2 presents the theoretical background and methodology. Section 3 details the empirical application of the model. Section 4 discusses the results and implications, while Section 5 concludes with suggestions for future research.

2. MATERIAL AND METHODS

This section presents fundamental ideas and operations related to FFS.

2.1. Fuzzy Fermatean Sets

FFS, a unique form of q-ROFS, was developed by Senapati and Yager in 2020. The unique q-ROFS idea, referred to as FFS, is defined with q = 3. FFS provides decision-makers with enhanced autonomy to voice their evaluations by indicating agreement (membership) or disagreement (non-membership) with perspectives regarding the current state of a specific topic.

Definition 1. Assume that $T = (\mu_T, v_T)$, $T_1 = (\mu_{T_1}, v_{T_1})$ and $T_2 = (\mu_{T_2}, v_{T_2})$ are three FFSs and $\omega > 0$, then some FFSs operators are presented as follows (Senapati and Yager, 2020):

$$T^c = (v_T, \mu_T) \quad (1)$$

$$T_1 \oplus T_2 = \left(\sqrt[3]{\mu_{T_1}^3 + \mu_{T_2}^3 - \mu_{T_1}^3\mu_{T_2}^3}, v_{T_1}v_{T_2}\right) \quad (2)$$

$$T_1 \otimes T_2 = \left(\mu_{T_1}\mu_{T_2}, \sqrt[3]{v_{T_1}^3 + v_{T_2}^3 - v_{T_1}^3 v_{T_2}^3}\right) \quad (3)$$

$$\omega T = \left(\sqrt[3]{1 - (1 - \mu_T^3)^\omega}, v_T^\omega\right) \quad (4)$$

$$T^\omega = \left(\mu_T^\omega, \sqrt[3]{1 - (1 - v_T^3)^\omega}\right) \quad (5)$$

Definition 2. The definitions of the score function (SF) is as follows:

$$SF = \mu_T^3 - v_T^3 \quad (6)$$

Definition 3. Assume that $T_i = (\mu_{T_i}, v_{T_i})$ (i=1,2,3,...,n) is a number of Fermatean fuzzy numbers (FFNs) and $w = (w_1, w_2, w_3, \dots, w_n)^T$ is weight vector of T_i. ($\sum_{i=1}^n w_i = 1$) (Mishra et al., 2023):

Fermatean fuzzy weighted average (FFWA) operator is:

$$FFWA(T_1, T_2, T_3, \dots, T_n) = \left(\sum_{i=1}^n w_i \mu_{T_i}, \sum_{i=1}^n w_i v_{T_i}\right) \quad (7)$$

Definition 5. Let $T = (\mu_T, v_T)$ be score functions for an FFS. $SF(T) \in [-1, 1]$. Hence, for an FFSs that consistently produces a positive defuzzified value, a positive score function is established in this context (Keshavarz-Ghorabaee et al., 2020):

$$SF^p(\tilde{X}_{ij}) = 1 + SF(\tilde{X}_{ij}) \quad (8)$$

Figure 1. Some definition related to FFS

2.2. Fermatean Fuzzy SWARA

Kersuliene et al. (2010) developed SWARA as a strategy based on subjective criteria weighting. SWARA enables decision-makers to set their priorities by evaluating prevailing situations. The FF-SWARA technique is delineated as follows [Ayyildiz et al., 2022; Korucuk et al., 2022].

Step 1. The judgments of decision-makers regarding each criterion are incorporated into a decision matrix by utilizing the linguistic terms depicted in Table 5.

Step 2. Find an aggregated decision matrix. We obtained aggregated decision matrix by deploying Fermatean Fuzzy Weighted Averaging (FFWA) operator given as Equation (7).

Step 3. The positive score value SC_j^+ for each criterion is estimated using Equation (9):

$$SC_j^+ = 1 + \vartheta_j^+ - \lambda_j^+ \quad (9)$$

Step 4. The criteria are ranked based on their positive score values in descending order.

Step 5. The relative importance of a positive score value for each criterion is determined by comparing it to the second preferred criterion, S criterion (j) and (j-1).

Step 6. The coefficient of each criterion is computed in accordance with Equation (10):

$$cc_j = \begin{cases} 1, & j = 1 \\ SC_j^+ + 1, & j > 1 \end{cases} \quad (10)$$

Step 7. The updated weights rw_j are computed based on the results in Step 6 as follows:

$$r\omega_j = \begin{cases} 1, & j = 1 \\ \frac{r\omega_{j-1}}{cc_j}, & i > 1 \end{cases} \quad (11)$$

Step 8. Equation (12) is employed to determine the final criteria weight w_j:

$$\omega_i = \frac{q_i}{\sum_{i=1}^{n} q_i} \quad (12)$$

Figure 2. Steps of the FF-SWARA method

2.3. Fermatean Fuzzy WASPAS

WASPAS is a hybrid method for multi-criteria decision-making that uses the Weighted Sum Method (WSM) and Weighted Product Method (WPM) to evaluate alternatives more thoroughly (Zavadskas et al., 2012). WASPAS is applicable and precise, especially in multi-criteria decision-making situations. WSM considers linear contributions, while WPM considers multiplicative criteria interactions. Thus, WASPAS combines the benefits of both methods for more equitable decision-making. The following steps comprise FF- WASPAS:

Step 1: Develop the FF decision matrix. During this step, each expert assesses n criteria using the linguistic terms presented in Table.

Table. The linguistic terms and FFSs.

Linguistic Terms	FFSs
Very very low (VVL)	(0.1, 0.9)
Very low (VL)	(0.1, 0.75)
Low (L)	(0.25, 0.6)
Medium low (ML)	(0.4, 0.5)
Medium (M)	(0.5, 0.4)
Medium high (MH)	(0.6, 0.3)
High (H)	(0.7, 0.2)
Very high (VH)	(0.8, 0.1)
Very very high (VVH)	(0.9, 0.1)

Step 2: Generate the matrix for aggregated decision-making matrix. Equation (7) is employed to calculate the comprehensive decision-making matrix using the Fermatean fuzzy weighted average (FFWA) aggregation operator.

Step 3: Obtain the normalized aggregated FF-decision matrix. Each element of the normalized decision matrix can be determined by the following formula:

$$N_{\text{ij}} = \begin{cases} X_{\text{ij}}(\mu_T, v_{\text{T}}) & if\ j \in \text{beneficial} \\ \text{X}_{\text{iJ}}^{C}(v_{\text{T}}, \mu_{\text{T}}) & if\ j \in \text{cost} \end{cases} \quad (13)$$

Step 4: The assessment of the WPM and the WSM measures for each alternative is as follows:

$$Z_i^1 = \sum_{j=1}^{m} w_j N_{\text{ij}} \quad (14)$$

$$Z_i^2 = \prod_{j=1}^{m} N_{ij}^{\ w_j} \quad (15)$$

Step 5: The WASPAS metric is derived by integrating multiplicative and additive approaches, as illustrated in the formula below:

$$Z_i = \lambda Z_i^1 + (1 - \lambda) Z_i^2 \quad (16)$$

Where λ [0, 1] is a combining parameter to integrate the WSM and WPM values.

Step 6: Determine the ranking order of alternatives according to the Z_i values.

Figure 3. Steps of the FF-WASPAS method

3. APPLICATION

The study utilized three expert opinions to ascertain the weightings of the parameters relevant to the sustainable supplier selection process. Experts were chosen among persons with expertise in procurement, sustainability, and SCM, reflecting varied corporate viewpoints. Each expert evaluated the four primary and eighteen secondary criteria based on their significance and quantitatively measured the influence of these factors on the decision-making process.

This study presented a decision model for sustainable supplier selection by merging the SWARA and WASPAS techniques under Fermatean fuzzy sets. In this context, the FF-SWARA method was employed to determine the criterion weights, while the findings derived from the FF-WASPAS method were compared to assess the alternatives.

The study examined sustainable supplier evaluation based on four primary criteria groups: Economic, Environmental, Social, and Governance. In the model, a total of 18 sub-criteria were established under these primary criteria. The organization of the primary and secondary criteria is delineated in Table 1 below, accompanied by a succinct discussion of each sub-criterion.

Table 1. Main and Sub-Criteria for Sustainable Supplier Selection

Criterion		**Explanation**	**Reference**
Economic			
Cost	C1	The total expenditure is incurred in the production, supply, and distribution of goods or services.	Heizer et al. (2017)
Financial Stability	C2	An organization's ability to maintain its revenue stream and cope with financial difficulties.	Higgins (2012)
Payment Terms	C3	The conditions that determine how businesses will pay for goods or services.	Narasimhan and Nair (2005)
Promotions and Discounts	C4	Price reductions and promotional offers are used to attract customers or increase sales.	Kotler and Keller (2015)
Supply Chain Flexibility	C5	The ability to withstand crises and ensure uninterrupted supply.	Christopher (2016)
Environmental			
Resource Efficiency	C6	Optimization of energy and water consumption, waste management, and recycling policies.	World Resources Institute (WRI). (2019)
Carbon Footprint	C7	Low-emission production and logistics processes, use of renewable energy.	Wiedmann and Minx (2008)
Sustainable Material Use	C8	Use of recycled or certified raw materials, reduction or elimination of hazardous chemicals.	European Commission. (2020)
Environmentally Friendly Products	C9	Products that do not harm nature, human health, or society, or that minimize such harm.	European Environment Agency (EEA). (2019)
Biodiversity Conservation	C10	Practices that prevent deforestation, sustainable agriculture, and water resource management.	CBD (Convention on Biological Diversity). (2011)
Social			
Working Conditions	C11	Fair wages, prohibition of forced labor, no child labor, and ensuring the health and safety of employees.	International Labour Organization (ILO). (2019)
Social Impact	C12	Contributing to local communities (education, employment, social projects). Supporting diversity and inclusivity without discrimination.	Porter and Kramer (2011)
Diversity and Inclusivity	C13	Ensuring an environment where all individuals, regardless of their characteristics, have equal rights and opportunities.	Ely and Thomas (2001)
Ethical Practices	C14	Anti-bribery and anti-corruption policies, transparent and fair trade practices.	Transparency International. (2020)
Governance			
Transparency and Traceability	C15	Ensuring that organizations' activities and processes are openly disclosed and subject to oversight.	Global Reporting Initiative (GRI). (2016)
Certificates and Standards	C16	Independent certification documents that demonstrate that businesses comply with specific quality and environmental management standards.	ISO (International Organization for Standardization). (2021)
On-Time Delivery	C17	A management approach that ensures that products or services reach customers within the agreed timeframes.	Stevenson (2018)
Risk Management	C18	Strategies that identify and mitigate environmental, social, and governance risks.	COSO (Committee of Sponsoring Organizations). (2017)

Step 1-2. Decision matrix is established as given Table 2:

Table 2. Expert judgments based on linguistic variables

	Criterion	DM 1	DM 2	DM 3
C1	Cost	MH	VH	VH
C2	Financial Stability	MH	H	H
C3	Payment Terms	VH	VH	H
C4	Campaigns and Discounts	VH	M	H
C5	Supply Chain Flexibility	VH	H	H
C6	Resource Efficiency	VH	M	MH
C7	Carbon Footprint	M	M	MH
C8	Sustainable Material Use	VH	M	H
C9	Environmentally Friendly Products	VH	M	H
C10	Biodiversity Conservation	VH	MH	MH
C11	Working Conditions	VH	MH	H
C12	Social Impact	VH	MH	MH
C13	Diversity and Inclusion	VH	MH	MH
C14	Ethical Practices	VH	MH	H
C15	Transparency and Traceability	VH	H	H
C16	Certifications and Standards	VH	VH	VH
C17	On-Time Delivery	VH	VH	VH
C18	Risk Management	H	H	H

Step 3. The aggregated decision matrix is obtained as shown Table 3:

Table 3. Aggregated decision matrix.

Criterion	DM1		DM2		DM3		Aggregated decision matrix	
C1	0,7	0,4	0,2	0,9	0,7	0,4	0,860	0,252
C2	0,7	0,4	0,3	0,8	0,7	0,4	0,773	0,330
C3	0,9	0,2	0,2	0,8	0,9	0,2	0,875	0,229
C4	0,9	0,2	0,5	0,8	0,9	0,2	0,809	0,311
C5	0,9	0,2	0,3	0,8	0,9	0,2	0,843	0,262
C6	0,9	0,2	0,5	0,7	0,9	0,2	0,784	0,342
C7	0,6	0,5	0,5	0,7	0,6	0,5	0,639	0,464
C8	0,9	0,2	0,5	0,8	0,9	0,2	0,809	0,311
C9	0,9	0,2	0,5	0,8	0,9	0,2	0,809	0,311
C10	0,9	0,2	0,4	0,7	0,9	0,2	0,799	0,317
C11	0,9	0,2	0,4	0,8	0,9	0,2	0,823	0,288
C12	0,9	0,2	0,4	0,7	0,9	0,2	0,799	0,317
C13	0,9	0,2	0,4	0,7	0,9	0,2	0,799	0,317
C14	0,9	0,2	0,4	0,8	0,9	0,2	0,823	0,288
C15	0,9	0,2	0,3	0,8	0,9	0,2	0,843	0,262
C16	0,9	0,2	0,2	0,9	0,9	0,2	0,900	0,200
C17	0,9	0,2	0,2	0,9	0,9	0,2	0,900	0,200
C18	0,8	0,3	0,3	0,8	0,8	0,3	0,800	0,300

Step 4-5-6-7. It is estimated the score value for each criterion, the criteria' relative significance (〚rs〛 _j), the coefficient (d_j), and the importance weight for each criterion as given in Table 4.

Table 4. Results of FF-SWARA

	The score value for each criterion	rs_j	d_j	S_j	ξ_j
C1	0,810		1,0000	1,0000	0,4909685
C2	0,713	0,8798	1,8798	0,5320	0,2611879
C3	0,829	1,1636	2,1636	0,2459	0,1207193
C4	0,750	0,9047	1,9047	0,1291	0,0633807
C5	0,790	1,0538	2,0538	0,0629	0,0308606
C6	0,721	0,9117	1,9117	0,0329	0,0161432
C7	0,580	0,8054	1,8054	0,0182	0,0089414
C8	0,750	1,2923	2,2923	0,0079	0,0039006
C9	0,750	1,0000	2,0000	0,0040	0,0019503
C10	0,739	0,9858	1,9858	0,0020	0,0009821
C11	0,767	1,0366	2,0366	0,0010	0,0004822
C12	0,739	0,9647	1,9647	0,0005	0,0002454
C13	0,739	1,0000	2,0000	0,0002	0,0001227
C14	0,767	1,0366	2,0366	0,0001	0,0000603
C15	0,790	1,0312	2,0312	0,0001	0,0000297
C16	0,861	1,0886	2,0886	0,0000	0,0000142
C17	0,861	1,0000	2,0000	0,0000	0,0000071
C18	0,743	0,8629	1,8629	0,0000	0,0000038

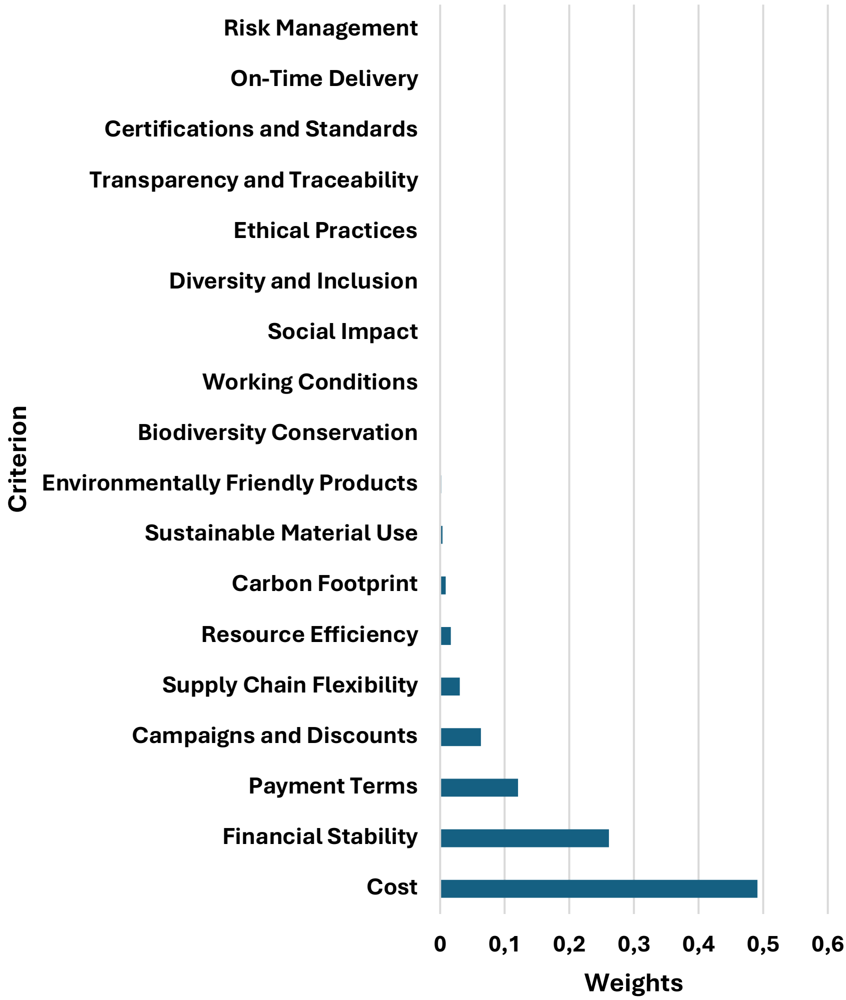

Figure 4. Weights of the criterion

Step 6. Each expert evaluates n criteria utilizing the linguistic terms listed in Table 5-6.

Table 5. FF-decision matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9
DM1_Supplier1	MH	VH	MH	MH	MH	MH	M	M	MH
DM1_Supplier2	H	VVH	VH	M	VH	VH	M	VH	VH
DM1_Supplier3	MH	VH	VH	ML	H	VH	M	H	VH
DM1_Supplier4	MH	M	M	MH	H	MH	M	L	M
DM1_Supplier5	MH	M	M	M	ML	ML	M	L	M
DM2_Supplier1	H	VH	VH	VH	VH	H	H	H	H
DM2_Supplier2	H	VVH	VH	M	VH	VH	VH	VH	VH
DM2_Supplier3	MH	VH	VH	ML	H	VH	VH	H	H
DM2_Supplier4	H	VH	VH	VH	VH	H	H	H	H
DM2_Supplier5	H	MH	H	H	H	H	H	H	H
DM3_Supplier1	H	VH	H	H	H	H	MH	MH	MH
DM3_Supplier2	VH	VVH	VH	MH	VH	VH	MH	VH	VH
DM3_Supplier3	H	VH	VH	M	H	VH	MH	H	H
DM3_Supplier4	H	MH	H	VH	VH	H	MH	M	M
DM3_Supplier5	H	MH	MH	MH	M	M	MH	M	MH
	C10	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**
DM1_Supplier1	M	MH	M	M	MH	MH	M	MH	MH
DM1_Supplier2	VH	VH	VH	VH	VH	VH	VVH	VVH	VH
DM1_Supplier3	H	VH	VH	VH	VH	H	H	H	H
DM1_Supplier4	ML	MH	M	M	MH	MH	M	M	M
DM1_Supplier5	ML	MH	M	M	MH	MH	M	L	M
DM2_Supplier1	H	H	VH	H	H	H	H	VH	VH
DM2_Supplier2	VH	VH	VH	VH	VH	VH	VH	VVH	VH
DM2_Supplier3	H	VH	VH	VH	VH	H	VH	H	H
DM2_Supplier4	H	H	VH	VH	H	H	H	VH	VH
DM2_Supplier5	H	H	H	H	H	H	H	H	H
DM3_Supplier1	MH	H	MH	MH	H	H	MH	H	H
DM3_Supplier2	VH	VH	VH	VH	VH	VH	VVH	VVH	VH
DM3_Supplier3	H	VH	VH	VH	H	H	H	H	H
DM3_Supplier4	M	MH	M	M	H	H	MH	MH	MH
DM3_Supplier5	M	H	MH	MH	H	H	MH	M	MH

Table 6. The evaluations of suppliers by each expert.

	C1		C2		C3		C4		C5		C6		C7		C8		C9	
DM1_Supplier1	0,6	0,3	0,8	0,1	0,6	0,3	0,6	0,3	0,6	0,3	0,6	0,3	0,5	0,4	0,5	0,4	0,6	0,3
DM1_Supplier2	0,7	0,2	0,9	0,1	0,8	0,1	0,5	0,4	0,8	0,1	0,8	0,1	0,5	0,4	0,8	0,1	0,8	0,1
DM1_Supplier3	0,6	0,3	0,8	0,1	0,8	0,1	0,4	0,5	0,7	0,2	0,8	0,1	0,5	0,4	0,7	0,2	0,8	0,1
DM1_Supplier4	0,6	0,3	0,5	0,4	0,6	0,3	0,7	0,2	0,7	0,2	0,6	0,3	0,5	0,4	0,25	0,6	0,5	0,4
DM1_Supplier5	0,6	0,3	0,5	0,4	0,5	0,4	0,5	0,4	0,4	0,5	0,4	0,5	0,5	0,4	0,25	0,6	0,5	0,4
DM2_Supplier1	0,7	0,2	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2
DM2_Supplier2	0,7	0,2	0,9	0,1	0,8	0,1	0,5	0,4	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1
DM2_Supplier3	0,6	0,3	0,8	0,1	0,8	0,1	0,4	0,5	0,7	0,2	0,8	0,1	0,8	0,1	0,7	0,2	0,7	0,2
DM2_Supplier4	0,7	0,2	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2
DM2_Supplier5	0,7	0,2	0,6	0,3	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2
DM3_Supplier1	0,7	0,2	0,8	0,1	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,6	0,3	0,6	0,3	0,6	0,3
DM3_Supplier2	0,8	0,1	0,9	0,1	0,8	0,1	0,6	0,3	0,8	0,1	0,8	0,1	0,6	0,3	0,8	0,1	0,8	0,1
DM3_Supplier3	0,7	0,2	0,8	0,1	0,8	0,1	0,5	0,4	0,7	0,2	0,8	0,1	0,6	0,3	0,7	0,2	0,7	0,2
DM3_Supplier4	0,7	0,2	0,6	0,3	0,7	0,2	0,8	0,1	0,8	0,1	0,7	0,2	0,6	0,3	0,5	0,4	0,5	0,4
DM3_Supplier5	0,7	0,2	0,6	0,3	0,6	0,3	0,6	0,3	0,5	0,4	0,5	0,4	0,6	0,3	0,5	0,4	0,6	0,3
	C10		**C11**		**C12**		**C13**		**C14**		**C15**		**C16**		**C17**		**C18**	
DM1_Supplier1	0,5	0,4	0,6	0,3	0,5	0,4	0,5	0,4	0,6	0,3	0,6	0,3	0,5	0,4	0,6	0,3	0,6	0,3
DM1_Supplier2	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,9	0,1	0,9	0,1	0,8	0,1
DM1_Supplier3	0,7	0,2	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2
DM1_Supplier4	0,4	0,5	0,6	0,3	0,5	0,4	0,5	0,4	0,6	0,3	0,6	0,3	0,5	0,4	0,5	0,4	0,5	0,4
DM1_Supplier5	0,4	0,5	0,6	0,3	0,5	0,4	0,5	0,4	0,6	0,3	0,6	0,3	0,5	0,4	0,25	0,6	0,5	0,4
DM2_Supplier1	0,7	0,2	0,7	0,2	0,8	0,1	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,8	0,1	0,8	0,1
DM2_Supplier2	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,9	0,1	0,8	0,1
DM2_Supplier3	0,7	0,2	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,7	0,2	0,8	0,1	0,7	0,2	0,7	0,2
DM2_Supplier4	0,7	0,2	0,7	0,2	0,8	0,1	0,8	0,1	0,7	0,2	0,7	0,2	0,7	0,2	0,8	0,1	0,8	0,1
DM2_Supplier5	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2
DM3_Supplier1	0,6	0,3	0,7	0,2	0,6	0,3	0,6	0,3	0,7	0,2	0,7	0,2	0,6	0,3	0,7	0,2	0,7	0,2
DM3_Supplier2	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,8	0,1	0,9	0,1	0,9	0,1	0,8	0,1
DM3_Supplier3	0,7	0,2	0,8	0,1	0,8	0,1	0,8	0,1	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2	0,7	0,2
DM3_Supplier4	0,5	0,4	0,6	0,3	0,5	0,4	0,5	0,4	0,7	0,2	0,7	0,2	0,6	0,3	0,6	0,3	0,6	0,3
DM3_Supplier5	0,5	0,4	0,7	0,2	0,6	0,3	0,6	0,3	0,7	0,2	0,7	0,2	0,6	0,3	0,5	0,4	0,6	0,3

Step 7. The aggregated decision-making matrix is estimated by using FFWA aggregation operator, as given in Table 7.

Table 7. The aggregated decision-making matrix.

	C1		C2		C3		C4		C5		C6	
Supplier1	0,67	0,23	0,80	0,10	0,70	0,20	0,70	0,20	0,70	0,20	0,67	0,23
Supplier2	0,73	0,17	0,90	0,10	0,80	0,10	0,53	0,37	0,80	0,10	0,80	0,10
Supplier3	0,63	0,27	0,80	0,10	0,80	0,10	0,43	0,47	0,70	0,20	0,80	0,10
Supplier4	0,67	0,23	0,63	0,27	0,70	0,20	0,77	0,13	0,77	0,13	0,67	0,23
Supplier5	0,67	0,23	0,57	0,33	0,60	0,30	0,60	0,30	0,53	0,37	0,53	0,37
	C7		C8		C9		C10		C12		C13	
Supplier1	0,60	0,30	0,60	0,30	0,63	0,27	0,60	0,30	0,67	0,23	0,63	0,27
Supplier2	0,63	0,27	0,80	0,10	0,80	0,10	0,80	0,10	0,80	0,10	0,80	0,10
Supplier3	0,63	0,27	0,70	0,20	0,73	0,17	0,70	0,20	0,80	0,10	0,80	0,10
Supplier4	0,60	0,30	0,48	0,40	0,57	0,33	0,53	0,37	0,63	0,27	0,60	0,30
Supplier5	0,60	0,30	0,48	0,40	0,60	0,30	0,53	0,37	0,67	0,23	0,60	0,30
	C14		C15		C16		C17		C18		C19	
Supplier1	0,60	0,30	0,67	0,23	0,67	0,23	0,60	0,30	0,70	0,20	0,70	0,20
Supplier2	0,80	0,10	0,80	0,10	0,80	0,10	0,87	0,10	0,90	0,10	0,80	0,10
Supplier3	0,80	0,10	0,77	0,13	0,70	0,20	0,73	0,17	0,70	0,20	0,70	0,20
Supplier4	0,60	0,30	0,67	0,23	0,67	0,23	0,60	0,30	0,63	0,27	0,63	0,27
Supplier5	0,60	0,30	0,67	0,23	0,67	0,23	0,60	0,30	0,48	0,40	0,60	0,30

Step 8. It is generated the normalized aggregated FF-decision matrix as shown in Table 8.

Table 8. The normalized aggregated decision matrix.

	C1		C2		C3		C4		C5		C6	
Supplier1	0,67	0,23	0,80	0,10	0,70	0,20	0,70	0,20	0,70	0,20	0,67	0,23
Supplier2	0,73	0,17	0,90	0,10	0,80	0,10	0,53	0,37	0,80	0,10	0,80	0,10
Supplier3	0,63	0,27	0,80	0,10	0,80	0,10	0,43	0,47	0,70	0,20	0,80	0,10
Supplier4	0,67	0,23	0,63	0,27	0,70	0,20	0,77	0,13	0,77	0,13	0,67	0,23
Supplier5	0,67	0,23	0,57	0,33	0,60	0,30	0,60	0,30	0,53	0,37	0,53	0,37
	C7		C8		C9		C10		C11		C12	
Supplier1	0,60	0,30	0,60	0,30	0,63	0,27	0,60	0,30	0,67	0,23	0,63	0,27
Supplier2	0,63	0,27	0,80	0,10	0,80	0,10	0,80	0,10	0,80	0,10	0,80	0,10
Supplier3	0,63	0,27	0,70	0,20	0,73	0,17	0,70	0,20	0,80	0,10	0,80	0,10
Supplier4	0,60	0,30	0,48	0,40	0,57	0,33	0,53	0,37	0,63	0,27	0,60	0,30
Supplier5	0,60	0,30	0,48	0,40	0,60	0,30	0,53	0,37	0,67	0,23	0,60	0,30
	C13		C14		C15		C16		C17		C18	
Supplier1	0,60	0,30	0,67	0,23	0,67	0,23	0,60	0,30	0,70	0,20	0,70	0,20
Supplier2	0,80	0,10	0,80	0,10	0,80	0,10	0,87	0,10	0,90	0,10	0,80	0,10
Supplier3	0,80	0,10	0,77	0,13	0,70	0,20	0,73	0,17	0,70	0,20	0,70	0,20
Supplier4	0,60	0,30	0,67	0,23	0,67	0,23	0,60	0,30	0,63	0,27	0,63	0,27
Supplier5	0,60	0,30	0,67	0,23	0,67	0,23	0,60	0,30	0,48	0,40	0,60	0,30

Step 9-10-11. The WSM and the WPM values are calculated by using Equations (14) and (15). Then, the WASPAS metric is estimated with $\lambda = 0.5$ utilizing Equation (16). Finally, the alternatives are ranked according to the Z_i values. As shown in Table 9, the outcomes of this stage consist of the final ranks, scores, and WSM, WPM, and WASPAS measurements.

Table 9. The results of the Fermatean fuzzy WASPAS.

Alternatives	QiS		QiP		Qi		T	RANK
Supplier1	0,672	0,248	0,645	0,289	0,659	0,268	1,001	3
Supplier2	0,869	0,104	0,852	0,260	0,860	0,182	1,067	1
Supplier3	0,744	0,169	0,724	0,331	0,734	0,250	1,004	2
Supplier4	0,666	0,263	0,631	0,295	0,649	0,279	1,000	4
Supplier5	0,608	0,317	0,572	0,371	0,590	0,344	1,000	5

According to the results, Supplier 2 was selected as the best alternative, with Supplier 3 in second place and Supplier 1 in third place.

4. CONCLUSION

The increasing emphasis on sustainability in global supply chains necessitates more sophisticated and comprehensive approaches to supplier evaluation. This study contributes to the growing body of literature by developing an integrated decision-making model that incorporates Fermatean Fuzzy SWARA and Fermatean Fuzzy WASPAS methods for the purpose of sustainable supplier selection. The proposed model provides a robust framework capable of handling complex decision environments where linguistic assessments, uncertainty, and expert judgment play a central role.

Unlike traditional supplier selection models that primarily emphasize economic efficiency, the framework developed in this study integrates environmental, social, and governance (ESG) dimensions into the decision process. Through a comprehensive literature review and expert input, 18 sub-criteria were identified under four main categories: economic, environmental, social, and governance. The FF-SWARA method enabled the determination of relative importance for each criterion in a structured and transparent manner, while the FF-WASPAS method allowed for the effective ranking of alternatives by combining additive and multiplicative scoring perspectives.

The model was applied to a real-world case involving five suppliers in the retail sector. Based on expert evaluations, the analysis revealed that "Certifications and Standards" and "On-Time Delivery" emerged as the most critical factors in sustainable supplier performance. These findings underscore the dual importance of regulatory compliance and operational reliability in achieving sustainability objectives. Supplier 2 was identified as the most sustainable alternative, followed by Suppliers 3 and 1, indicating that a balanced performance across all ESG dimensions plays a decisive role in supplier preference.

From a managerial perspective, this study offers a decision support tool that enhances the transparency, accountability, and effectiveness of supplier selection processes. The integrated fuzzy MCDM approach allows procurement teams to systematically incorporate qualitative judgments and sustainability considerations, which are often overlooked or undervalued in conventional models. Moreover, the Fermatean fuzzy logic framework significantly improves the model's capability to capture the hesitation and uncertainty commonly found in expert assessments.

In terms of methodological contribution, the study demonstrates the practical applicability of Fermatean fuzzy extensions of both SWARA and WASPAS—two widely accepted MCDM techniques. While previous studies have utilized classical or intuitionistic fuzzy versions of these methods, this research is among the first to apply their Fermatean fuzzy counterparts in an integrated form within the sustainability context. This not only enhances the precision of the decision-making process but also broadens the potential for future research using advanced fuzzy set theories.

There are several avenues for extending this research. Future studies could incorporate dynamic weighting mechanisms to reflect evolving priorities in sustainability, or employ larger expert panels to increase the robustness of the results. In addition, comparative analyses with other fuzzy models such as spherical fuzzy sets, q-ROFS, or neutrosophic sets could offer insights into methodological performance under different uncertainty environments. Sector-specific applications, such as in manufacturing, logistics, or healthcare, may also reveal industry-dependent sustainability priorities that influence supplier selection differently.

In conclusion, the proposed model offers both theoretical and practical value by aligning supplier selection with sustainability goals in a structured, data-informed, and uncertainty-sensitive manner. It is hoped that this framework will support decision-makers in making more responsible, transparent, and sustainable procurement decisions that extend beyond economic efficiency to include broader societal and environmental impacts

REFERENCES

Atanassov, K.T., 1986. Intuitionistic fuzzy sets, Fuzzy Sets and Systems, 20 (1), 87-96.

Awasthi, A., Chauhan, S. S., & Goyal, S. K. (2010). A fuzzy multicriteria approach for evaluating environmental performance of suppliers. *International Journal of Production Economics, 126*(2), 370–378.

Büyüközkan, G., & Çifçi, G. (2011). A novel fuzzy multi-criteria decision framework for sustainable supplier selection with incomplete information. *Computers in Industry, 62*(2), 164–174.

Camci, A., Ertürk, M.E., Gül, S., (2022). A Novel Fermatean Fuzzy Analytic Hierarchy Process Proposition and Its Usage for Supplier Selection Problem in Industry 4.0 Transition. In: Garg, H. (eds) q-Rung Orthopair Fuzzy Sets. Springer, Singapore.

CBD (Convention on Biological Diversity). (2011). Biodiversity and Sustainable Agriculture.

Christopher, M. (2016). Logistics & Supply Chain Management. Pearson UK.

COSO (Committee of Sponsoring Organizations). (2017). Enterprise Risk Management—Integrating with Strategy and Performance.

Cuong, B. C., Kreinovich, V. (2013). Picture fuzzy sets—a new concept for computational intelligence problems, in Proceeding of the 3rd World Congress on Information and Communication Technologies, December 15–18 (Hanoi, Vietnam, 2013), 1–6.

Elkington, J. (1997). *Cannibals with forks: The triple bottom line of 21st century business*. Capstone Publishing.

Ely, R. J., & Thomas, D. A. (2001). Cultural Diversity at Work: The Effects of Diversity Perspectives on Work Group Processes and Outcomes. Administrative Science Quarterly, 46(2), 229-273.

European Commission. (2020). Sustainable Materials Management.

European Environment Agency (EEA). (2019). Circular Economy and Sustainable Materials Management.

Global Reporting Initiative (GRI). (2016). Standards for Transparency and Reporting.

Govindan, K., Rajendran, S., Sarkis, J., & Murugesan, P. (2015). Multi criteria decision making approaches for green supplier evaluation and selection: A literature review. *Journal of Cleaner Production, 98*, 66–83.

Heizer, J., Render, B., & Munson, C. (2017). Operations Management: Sustainability and Supply Chain Management. Pearson.

Higgins, R. C. (2012). Analysis for Financial Management. McGraw-Hill/Irwin.

International Labour Organization (ILO). (2019). Decent Work and Working Conditions.

ISO (International Organization for Standardization). (2021). ISO 14001 Environmental Management.

Kersuliene, V., Zavadskas, E. K., & Turskis, Z. (2010). Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (SWARA). *Journal of Business Economics and Management, 11*(2), 243–258.

Keshavarz-Ghorabaee, M., Amiri, M., Hashemi-Tabatabaei, M., Zavadskas, E. K., & Kaklauskas, A. (2020). A new decision-making approach based on Fermatean fuzzy sets and WASPAS for green construction supplier evaluation. Mathematics, 8(12), 2202.

Kirişci, M. (2022). Fermatean hesitant fuzzy sets with medical decision making application.

Kirişci, M. (2023). New cosine similarity and distance measures for Fermatean fuzzy sets and TOPSIS approach. Knowledge and Information Systems, 65(2), 855-868.

Kotler, P., & Keller, K. L. (2015). Marketing Management. Pearson.

Kutlu Gündoğdu, F., Kahraman, C. (2019). Spherical fuzzy sets and spherical fuzzy TOPSIS method. Journal of intelligent & fuzzy systems, 36(1), 337-352.

Mishra, A. R., Chen, S. M., & Rani, P. (2023). Multicriteria decision making based on novel score function of Fermatean fuzzy numbers, the CRITIC method, and the GLDS method. Information Sciences, 623, 915-931.

Narasimhan, R., & Nair, A. (2005). The Role of Payment Terms in Supplier-Buyer Relationships. Journal of Business Logistics, 26(2), 65-88.

Nikou, S., & Meier, A. (2021). Sustainable supplier selection using hybrid SWARA and WASPAS methods. *Sustainability, 13*(12), 6564.

Porter, M. E., & Kramer, M. R. (2011). Creating Shared Value. Harvard Business Review.

Rezaei, J., & Ortt, R. (2018). Multi-criteria supplier segmentation using a fuzzy preference relations-based AHP. *Expert Systems with Applications, 95*, 84–106. https://doi.org/10.1016/j.eswa.2017.11.002

Senapati, T., & Yager, R. R. (2020). Fermatean fuzzy sets. Journal of Ambient Intelligence and Humanized Computing, 11, 663-674.

Simic, V., Ebadi Torkayesh, A., & Ijadi Maghsoodi, A. (2022). Locating a disinfection facility for hazardous healthcare waste in the COVID-19 era: a novel approach based on Fermatean fuzzy ITARA-MARCOS and random forest recursive feature elimination algorithm. Annals of Operations Research.

Stevenson, W. J. (2018). Operations Management. McGraw-Hill Education.

Transparency International. (2020). Anti-Corruption Principles.

Wiedmann, T., & Minx, J. (2008). A Definition of 'Carbon Footprint'. Ecological Economics, 67(1), 115-124.

World Resources Institute (WRI). (2019). Corporate Resource Efficiency Practices.

Yager, R. R. (2014). Pythagorean membership grades in multicriteria decision making. IEEE Transactions on Fuzzy Systems, 22(4), 958-965.

Zavadskas, E. K., Turskis, Z., & Kildienė, S. (2014). State of art surveys of overviews on MCDM/MADM methods. *Technological and Economic Development of Economy, 20*(1), 165–179.

Zavadskas, E. K., Turskis, Z., Antucheviciene, J., & Zakarevicius, A. (2012). Optimization of weighted aggregated sum product assessment. Elektronika ir elektrotechnika, 122(6), 3-6.