

Article

A Fermatean Fuzzy SWARA-TOPSIS Based Approach for Sustainable Packaging Selection in Logistics Operations

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Abstract

This study presents an integrated Multi-Criteria Decision-Making (MCDM) approach to select the most suitable sustainable packaging for logistics operations under uncertainty. The aim of this study is to identify the most suitable eco-friendly packaging options for reducing packaging waste, by considering several criteria. The methodology combines the SWARA and TOPSIS methods within a Fermatean Fuzzy Set (FFS) framework to address the ambiguity in expert evaluations and the qualitative nature of decision-making criteria. The research considers various sustainable packaging alternatives, including recycled cardboard, recycled plastic, biodegradable plastic, and compostable plastic, while incorporating criteria such as production cost, environmental impact, reusability, and material specifications. The approach offers a robust and comprehensive decision-making tool for companies aiming to improve sustainability in their logistics operations while mitigating the environmental impact of packaging waste. The results demonstrate that the direct incorporation of fuzzy numbers notably influences the ranking outcomes compared to traditional methods, and comparing the considered approach with different MCDM methods yields various recommendations for sustainable packaging selection.

Keywords: sustainable packaging; sustainable development goals; multi-criteria decision-making; Fermatean fuzzy SWARA; Fermatean fuzzy TOPSIS

1. Introduction

The United Nations introduced the Sustainable Development Goals (SDGs) to foster global sustainability across economic, social, and environmental dimensions [1]. The 17 interconnected goals are designed to advance sustainable practices by 2030 [2]. Among SDGs, Goal 12: Responsible Consumption and Production, aims to alter production and consumption patterns to preserve the planet and the livelihoods of current and future generations. The goal directly contributes to targets such as substantially reducing waste generation through prevention, reduction, recycling, and reuse (12.5) and encourages large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle (12.6).

Within the scope of Target 12.5, the packaging sector has a critical role that requires urgent and systematic intervention due to its significant and rapidly growing contribution to global waste streams. Packaging refers to the materials or containers used to identify and distinguish a product, facilitate its transportation and distribution, ensure proper storage, promote the product, and enable its correct use [3]. The primary logistical function of packaging is to safeguard the product as it moves through distribution channels. While this may incur additional packaging costs, it helps minimize damage, spoilage, theft, or the loss of goods [4]. Population and consumption growth have made packaging a significant



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environmental concern, as higher consumption leads to greater solid waste, industrial waste, and greenhouse gas emissions [5]. As a result, the packaging industry has a key role in maintaining environmental protection and sustainable development. In specific, after a short first-use life-cycle, 95% of the value of plastic packaging materials, amounting to \$80–120 billion annually, is lost to the economy [6]. The total packaging volume increased from 66 million tonnes in 2009 to 84 million in 2021 [7]. Each European produced 188.7 kg of packaging waste in 2021, and there is an expectation for a rise to 209 kg by 2030 [8]. To alleviate the negative effects of packaging waste, the UN Parliament and Council reached an agreement on rules to reduce, reuse, and recycle packaging with targets (5% by 2030, 10% by 2035, and 15% by 2040) [9]. However, Kluczek et al. [10] stated that packaging companies are still distant from making significant contributions toward achieving specific sustainability goals.

Sustainable packaging (also called eco-friendly or environmentally friendly packaging) is an approach that does not consider only the material or design of packages. According to the Sustainable Packaging Coalition (SPC), sustainable packaging (i) supports the use of recycled materials and/or renewable feedstocks, (ii) is designed for reusability, recyclability, or compostability, (iii) provides labels with suitable end-of-life instructions, (iv) prefers reuse and refill options, and (v) invests in the expansion of recycling and composting infrastructure, as well as in improving collection systems and access [11]. Governments and consumers are leading companies to redesign product packaging to be more eco-friendly. For example, Nestlé reached 86.6% of packaging that is reusable, recyclable, or compostable, with a 14.9% reduction in virgin plastic usage in 2023 and also aimed to make 95% of its plastic packaging recyclable [12].

Since 2018, following the tightening of plastic waste import restrictions across several Asian countries, Turkey has emerged as the primary destination for Europe's plastic waste exports, receiving more than half of the EU's total shipments. This shift reflects not only regulatory changes in Asia but also Europe's persistent structural shortcomings in managing its own recycling capacity. As an emerging market with limited waste management infrastructure, Turkey has become a critical hub for plastic waste flows [13]. Consequently, the environmental and financial burdens associated with non-recyclable plastic waste are increasingly externalized to Turkey, underscoring the urgent need for stronger regulatory coordination and enforcement at both European and international levels. Although Turkey is the sixth largest player of Europe's packaging industry, with a size of \$28 billion [14], Turkish packaging manufacturers have recently complied with environmental legislation and regulations (i.e., Packaging and Packaging Waste Management Legislation). According to Packaging and Packaging Waste Management Legislation published in 2021, packaging manufacturers are required to use at least eight percent recycled plastic in their products [15].

Although academics and practitioners have a developing interest in sustainable packaging, a limited number of studies consider sustainable packaging [16–19]. Several sustainable packaging types (e.g., recycled cardboard and paper, recycled plastic packaging, biodegradable plastic packaging, etc.) have been designed and used in logistics operations [20]. Selecting a suitable alternative among various sustainable packaging types is a challenging and time-consuming process for decision-makers who should consider unpredictable events and factors [21]. Choosing the best alternative is directly affected by many criteria related to sustainable packaging. A company obtains several advantages such as cost reduction, increased competitiveness, and a stable distribution process with the right decision to select the best alternative. Multi-criteria decision methods (MCDMs) can help decision-makers determine the best alternative considering various criteria among different sustainable packaging types [22]. A common MCDM begins with identifying different criteria from the literature and/or experts. Then, it assigns a

total score to each alternative to rank them. Experts usually evaluate alternatives with subjective judgments that cause vagueness and imprecise data (i.e., linguistic variables) to be handled by decision-makers. To eliminate the negative effects of linguistic variables in the decision process, the fuzzy set theory was first suggested by Zadeh [23]. Fuzzy sets provide more accurate information, to choose the best alternative considering related criteria.

The Fuzzy Fermatean Set (FFS), originally introduced as an extension of intuitionistic and Pythagorean fuzzy sets, provides greater flexibility in modeling uncertainty. Unlike intuitionistic fuzzy sets, where the sum of membership and non-membership degrees is constrained to be less than or equal to 1, and Pythagorean fuzzy sets, where the squared sum of these degrees must not exceed 1, FFS allows the sum of the cubes of membership and non-membership degrees to be less than or equal to 1 [24]. The relaxed constraint enlarges the permissible decision space and enables experts to express their opinions with higher freedom and reduced distortion [25]. This characteristic is particularly important in sustainable packaging selection problems, where experts may feel uncertain about alternatives due to conflicting environmental, economic, and social considerations. The FFS structure alleviates this uncertainty more effectively by providing a wider domain for expressing uncertainty without violating logical consistency. Consequently, it enhances the reliability and representativeness of aggregated expert judgments.

This study addressed an MCDM method to incorporate expert judgment through the SWARA method, enabling more context-sensitive and strategically aligned weighting. Furthermore, it preserves the fundamental strength of TOPSIS—simultaneous consideration of distances to both positive and negative ideal solutions—thereby providing a clear geometric interpretation of alternative rankings. By integrating the high uncertainty modeling capacity of Fermatean fuzzy sets, the flexibility of expert-based SWARA weighting, and the robust compromise logic of TOPSIS, Fermatean-SWARA-TOPSIS offers a more comprehensive, adaptable, and theoretically powerful decision-making framework.

This study aims to help companies engaged in sustainable packaging activities in determining the most appropriate type of sustainable packaging by considering a set of predefined criteria. This research not only proposes a methodological framework but also addresses the sustainable packaging selection problem in a manner that contributes to mitigating the negative environmental impacts of packaging waste, which represents a significant source of environmental pollution. In addition, the study seeks to suggest various practical insights to companies and governments to underline the importance of sustainable packaging.

The remainder of the study is structured as follows. Section 2 addresses some related studies in the sustainable packaging literature. Section 3 provides background information about the considered methodologies. Section 4 introduces the FF-SWARA-TOPSIS methodology for the considered problem. Section 5 presents the case study of the sustainable packaging selection problem. Section 6 suggests critical managerial implications for decision makers in logistics and supply chain operations striving for sustainability. Section 7 concludes the study and suggests directions for new research.

2. Literature Review

This section provides a brief literature review of packaging selection problems and MCDMs with Fermatean fuzzy consideration. Then, the contribution of the study has been presented and research gaps have been identified.

2.1. Packaging Selection Problem

In logistics operations, packaging is typically structured at two hierarchical levels: primary and secondary. Primary packaging is in direct contact with the product, serving both protective and containment functions, whereas secondary packaging is designed to consol-

idate multiple primary packages for handling, storage, and transportation purposes [26]. The dimensions of packaging significantly influence the efficiency of warehouse space utilization and transportation capacity. Optimized packaging design can contribute to reduced waste management and disposal costs, while lightweight materials may lower transportation expenses [27,28]. Moreover, enhanced protective features in packaging reduce the likelihood of product damage throughout the distribution process [18].

Packaging often becomes waste before the product reaches its end-of-life stage. Consequently, selecting an appropriate packaging solution presents a significant challenge, as it must balance the need for cost-efficiency with the imperative of environmental protection. Table 1 provides a brief review of the literature on the packaging selection problem.

Table 1. A brief literature review of packaging selection problem.

Author(s)	Aim	Method	Uncertainty	Sustainability Concern
Calderon et al. [29]	To illustrates the effectiveness of the LCA approach in identifying more sustainable alternatives within the ready meals food sector.	LCA	-	Environmental impact
Pasqualino et al. [30]	To assess the environmental impact associated with the production and disposal of various types of beverage packaging.	LCA	-	Environmental impact
Meneses et al. [31]	To gain a deeper understanding of the environmental implications throughout the life cycle of milk.	LCA	-	Environmental impact
Palsson et al. [18]	To develop an evaluation model for selecting supply chain packaging systems, focusing on sustainability.	Analytical	-	Carbon emission
Stanujkic et al. [32]	To suggest an effective MCDM approach for selecting suitable packaging.	MCDM	-	-
Almeida et al. [16]	To introduce environmental accounting based on “emergy” as a tool to support material selection.	Analytical	-	Environmental impact
Gurralla et al. [17]	To select suitable edible packaging by employing a Hybrid MCDM.	MCDM	-	Eco-friendly product
S. Mungan & Aydın [33]	To present a hybrid MCDM to select suitable tertiary package alternative in logistics.	MCDM	-	-
Sangkhiew et al. [34]	To compare and select package alternatives in cold chain logistics	MCDM	-	-
Rane et al. [35]	To rank barriers to reusable packaging adoption process.	MCDM	Triangular Fuzzy	Reuse
Verros et al. [36]	To determine how packaging design affects the amount of emission from material and transport by using a LCA-based approach.	LCA	-	Emission

In the literature, Life Cycle Assessment (LCA), mathematical, and MCDM are the primary approaches to evaluate the best packaging option in the packaging selection problem. LCA is a methodological approach used to evaluate the environmental factors and impacts related with processes or products [37]. This is achieved through the compilation of an inventory that details relevant energy and material inputs, as well as environmental emissions, throughout the entire life cycle of the product under consideration. Studies employing the

LCA approach focus on selecting suitable packaging options to reduce the negative effect of package-related waste on the environment. For instance, Calderon et al. [29] show that implementing biopolymer packaging systems in the food sector helps companies reduce the amount of package waste. Pasqualino et al. [30] conclude that larger packages are more environmentally friendly than smaller ones considering product losses in beverage packaging. Meneses et al. [31] reach similar conclusions with Pasqualino et al. [30] about the size of packages for milk packaging cases and aseptic cartons present the lowest environmental impacts considering all indicators. Verros et al. [36] conclude that transportation-related emission levels are directly influenced by the optimization of product dimensions through packaging design.

Apart from the LCA approach, Palsson et al. [18] and Almeida et al. [16] analytically examine packaging alternatives. Palsson et al. [18] evaluates two different packaging systems (i.e., secondary packages) considering the carbon emission of each alternative. Results show that returnable packaging comes with an additional cost compared to one-way packaging. Almeida et al. [16] introduces an environmental accounting-based approach to select the best packaging options in the soft drink sector.

Few studies employ MCDM-based approaches in the packaging selection problem. As an early attempt, Stanujkic et al. [32] use the SWARA approach to select suitable packaging designs among various variants. Gurralla et al. [17] propose a CRITIC-TOPSIS approach to select eco-friendly packaging (i.e., biopolymer) options considering several criteria. S. Mungan & Aydın [33] suggest an AHP-DEMATEL-based hybrid approach to determine convenient packaging options among large cardboard, small cardboard, and Styrofoam boxes. Sangkhiew et al. [34] compare packaging options for fruit delivery in the cold supply chain by employing Entropy Weight and TOPSIS approach. Rane et al. [35] consider a triangular fuzzy numbers integrated MCDM methodology to rank barriers to reusable packaging adoption.

2.2. Fermatean Fuzzy Based MCDMs

FFSs have received growing interest from academics in the MCDM literature since Senapati [24] introduced the score function and accuracy function, and defined several operators for calculating with FFS. In recent years, FFSs have been implemented in various MCDM methods (e.g., TOPSIS, DEMATEL, etc.) and employed in different selection problems (e.g., location, technology, and supply chain actor selection) related to SDGs. Table 2 presents a brief literature review of MCDMs in the Fermatean fuzzy environment.

Table 2. A brief literature review of MCDMs related to SDGs in the Fermatean fuzzy environment.

Author(s)	Method	Problem	Application Area
Mishra et al. [38]	WASPAS	Waste disposal location selection	Healthcare sector
Mishra et al. [39]	CRITIC-EDAS	Sustainable third-party reverse logistics provider selection	Logistics
Rani et al. [40]	ARAS-MEREC	Food waste treatment technology selection	Food sector
Kao et al. [41]	DEMATEL	Sustainable development evaluation ranking	Manufacturing sector
Karuppiah et al. [42]	DEMATEL	Green Economy practices ranking	SDGs
Luo & Liu [43]	MULTIMOORA	Green region selection	Regions in China
Yang et al. [44]	TOPSIS	Green low-carbon port selection	Shipping ports
Görçün et al. [45]	SWARA-COPRAS	Sustainable logistics service provider selection	Healthcare sector
Karuppiah & Sanka [46]	AHP-DEMATEL-TOPSIS	E-waste mitigation strategies ranking	E-waste recycling sector
Seikh & Mandal [47]	SWARA-PROMETHEE II	Bio-medical waste center selection	Healthcare sector

Table 2. Cont.

Author(s)	Method	Problem	Application Area
Moktadir & Ren [48]	Delphi-TODIM-WINGS	Solid waste strategies ranking	Tannery sector
Ayyildiz & Erdogan [49]	SWARA-TOPSIS	Autonomous vehicle parking lot selection	Parking area sector
Gao et al. [50]	BWM-VIKOR	Waste treatment technology selection	Healthcare sector
Golui et al. [51]	TOPSIS	Electric vehicle selection	Automotive sector
Dutta et al. [52]	MEREC-SWARA-ORCA	Waste treatment technology selection	Plastic waste disposal sector
Pathak & Sen [53]	Entropy-SWARA-WASPAS	Recycling plant ranking	Household waste
Behera & Panda [54]	SWARA-LOPCOW-EDAS	Renewable energy ranking	Energy sector
Saranya & Jayanthi [55]	MEREC-MULTIMOORA	Waste treatment technology selection	Healthcare sector
Liu et al. [56]	AHP-MAIRCA	Renewable energy ranking	Energy sector

Studies have implemented FFS into MCDM to solve ranking and selection problems in the literature. Ranking problems usually aim to rank various criteria for the considered topic. Kao et al. [41] focus on a comprehensive framework for assessing enterprise sustainability, by ranking eight criteria covering economic, social, environmental, institutional, and risk management aspects. Karuppiah et al. [42] aim to rank twenty critical factors for green economy practices, categorized into five dimensions related to sustainable development goals in various industries. Karuppiah & Sanka [46] propose a hybrid MCDM to rank five e-waste mitigation strategies in India. The results show that the government's establishment of infrastructure for modern e-waste management is the most suitable strategy for India. Moktadir & Ren [48] determine the ranking of environmental, social, and governance practices implementing challenges for tannery solid waste management in Bangladesh. Pathak & Sen [53] suggest a new distance measure for solving MCDM problems and apply it in recycling plant ranking problem. Behera & Panda [54] consider a hybrid MCDM to rank five renewable energy sources in Turkey. Liu et al. [56] introduce new interval-valued Fermatean fuzzy sets to select the best sustainable energy alternative.

Selection problems, on the other hand, focus on determining the suitable alternative for the considered problem. Mishra et al. [38] suggest an FFS integrated WASPAS method to select healthcare waste disposal locations considering five environmental-related, two economic-related, and three social-related criteria in India. Mishra et al. [39] propose a hybrid Multi-Criteria Decision-Making (MCDM) methodology for selecting sustainable third-party reverse logistics providers in India, considering thirteen criteria encompassing environmental, economic, and social dimensions. Rani et al. [40] propose an integrated ARAS methodology that combines the entropy measure, Heronian mean operators, and the MEREC technique for selecting food waste treatment technologies. Luo & Liu [43] suggest a hesitant FFS MULTIMOORA method to determine the green development level of various regions in China. The study considers fifteen criteria encompassing ecological construction, green environment, and circular economy factors. Yang et al. [44] firstly introduce Fermatean fuzzy integrated weighted average distance and TOPSIS method in selecting green low-carbon port. Görçün et al. [45] integrate interval-valued Fermatean fuzzy sets into a hybrid MCDM method to choose a suitable medical waste disposal and logistics company. Seikh & Mandal [47] propose interval-valued Fermatean fuzzy sets with Dombi aggregation operators, a hybrid MCDM for bio-medical waste management company selection problem. Ayyildiz & Erdogan [49] suggest a Fermatean fuzzy SWARA-TOPSIS approach based on the SCOR model (i.e., a hierarchical framework comprising four levels that dissects the supply chain into its individual processes) for autonomous vehicle (e.g., hybrid and/or electric) parking lot selection problem. Gao et al. [50] consider eight criteria to select suitable waste treatment technology in China. Golui et al. [51] propose a correlation-based FF-TOPSIS approach for the electric vehicle selection problem. Dutta et al. [52] propose a Fermatean fuzzy MEREC-SWARA-OCRA approach to select the best waste treatment technology.

Saranya & Jayanthi [55] integrate cubic Fermatean fuzzy sets into a hybrid MCDM method to select the best waste treatment option in the health sector.

A review of the existing literature indicates that no previous study has incorporated an FFS-integrated MCDM framework into a sustainable packaging selection problem within the logistics context. Furthermore, to the best of our knowledge, sustainable secondary packaging has not previously been examined in the packaging selection literature. Accordingly, this study contributes to the field by systematically addressing the sustainable packaging selection problem in a manner that supports the mitigation of the negative environmental impacts of packaging waste, which constitutes a significant source of environmental pollution. Furthermore, the study provides practical implications and policy-oriented insights for both companies and governmental authorities, emphasizing the strategic importance of adopting sustainable packaging solutions.

3. Preliminaries

Introduced by Senapati [24], an FFS is an approach designed to handle uncertain information with greater flexibility and efficiency. Like Intuitionistic Fuzzy Sets (IFS) and Pythagorean Fuzzy Sets (PFS), an FFS consists of two primary components: membership and non-membership degrees. The following are some key concepts related to FFS:

Definition 1. Let X be a universe of discourse. A Fermatean fuzzy set $\mathcal{F}$ in X is an object having the form

$$\mathcal{F} = \{ \langle x, \alpha_{\mathcal{F}}(x), \beta_{\mathcal{F}}(x) \rangle : x \in X \} \quad (1)$$

where $\alpha_{\mathcal{F}}(x) : X \rightarrow [0, 1]$ and $\beta_{\mathcal{F}}(x) : X \rightarrow [0, 1]$ including the condition

$$0 \leq (\alpha_{\mathcal{F}}(x))^3 + (\beta_{\mathcal{F}}(x))^3 \leq 1, \quad (2)$$

for all $x \in X$. The numbers $\alpha_{\mathcal{F}}(x)$ and $\beta_{\mathcal{F}}(x)$ denote, respectively, the degree of membership and the degree of nonmembership of the element x in the set $\mathcal{F}$.

For any FFS $\mathcal{F}$ and $x \in X$

$$\pi_{\mathcal{F}}(x) = \sqrt[3]{1 - (\alpha_{\mathcal{F}}(x))^3 - (\beta_{\mathcal{F}}(x))^3} \quad (3)$$

is identified as the degree of indeterminacy of x to $\mathcal{F}$. In the interest of simplicity, the symbol $\mathcal{F} = (\alpha_{\mathcal{F}}, \beta_{\mathcal{F}})$ for the FFS $\mathcal{F} = \{ \langle x, \alpha_{\mathcal{F}}(x), \beta_{\mathcal{F}}(x) \rangle : x \in X \}$ has been presented.

Figure 1 illustrates a comparison between intuitionistic, Pythagorean, and FFSs. Here, Intuitionistic membership grades (IMGs) are all points beneath the line $x + y \leq 1$, the Pythagorean membership grades (PMGs) are all points with $x^2 + y^2 \leq 1$, and the Fermatean membership grades (FMGs) are all points with $x^3 + y^3 \leq 1$. As a result, FFS enables higher non-membership degrees than both IFS and PFS.

Definition 2. $\mathcal{F} = (\alpha_{\mathcal{F}}, \beta_{\mathcal{F}})$ function of $\mathcal{F}$ can be represented as

$$\text{score}(\mathcal{F}) = \alpha_{\mathcal{F}}^3 - \beta_{\mathcal{F}}^3, \quad (4)$$

where $\text{score}(\mathcal{F}) \in [-1, 1]$.

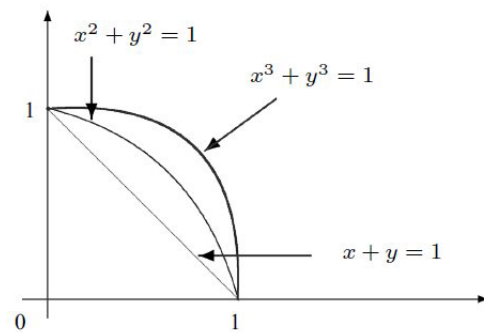


Figure 1. A comparison among FMGs, PMGs and IMGs.

Definition 3. Let $\mathcal{F}_1 = (\alpha_{F_1}, \beta_{F_1})$ and $\mathcal{F}_2 = (\alpha_{F_2}, \beta_{F_2})$ be two FFSs, $\text{score}(\mathcal{F}_1)$ and $\text{score}(\mathcal{F}_2)$ be the score function of $\mathcal{F}_1$ and $\mathcal{F}_2$ respectively, then:

1. If $\text{score}(\mathcal{F}_1) < \text{score}(\mathcal{F}_2)$, then $\mathcal{F}_1 < \mathcal{F}_2$;
2. If $\text{score}(\mathcal{F}_1) > \text{score}(\mathcal{F}_2)$, then $\mathcal{F}_1 > \mathcal{F}_2$;
3. If $\text{score}(\mathcal{F}_1) = \text{score}(\mathcal{F}_2)$, then $\mathcal{F}_1 \sim \mathcal{F}_2$.

Definition 4. Let $\mathcal{F} = (\alpha_F, \beta_F)$ be an FFS, then the accuracy function regarding $\mathcal{F}$ can be described as follows:

$$\text{acc}(\mathcal{F}) = \alpha_F^3 + \beta_F^3. \quad (5)$$

where $\text{acc}(\mathcal{F}) \in [0, 1]$.

Clearly, $\text{acc}(\mathcal{F}) \in [0, 1]$. In fact $0 \leq \text{acc}(\mathcal{F}) = \alpha_F^3 + \beta_F^3 \leq 1$. If the value of $\text{acc}(\mathcal{F})$ is increasing, the accuracy of FFS $\mathcal{F}$ will be increased, as well.

Definition 5. Let $\mathcal{F}_1 = (\alpha_{F_1}, \beta_{F_1})$ and $\mathcal{F}_2 = (\alpha_{F_2}, \beta_{F_2})$ be two FFSs. $\text{score}(\mathcal{F}_i)$ and $\text{acc}(\mathcal{F}_i)$ ($i = 1, 2$) are the score values and accuracy values of $\mathcal{F}_1$ and $\mathcal{F}_2$, respectively, then:

1. If $\text{score}(\mathcal{F}_1) < \text{score}(\mathcal{F}_2)$, then $\mathcal{F}_1 < \mathcal{F}_2$;
2. If $\text{score}(\mathcal{F}_1) > \text{score}(\mathcal{F}_2)$, then $\mathcal{F}_1 > \mathcal{F}_2$;
3. If $\text{score}(\mathcal{F}_1) = \text{score}(\mathcal{F}_2)$, then;
 - (i) If $\text{acc}(\mathcal{F}_1) < \text{acc}(\mathcal{F}_2)$, then $\mathcal{F}_1 < \mathcal{F}_2$;
 - (ii) If $\text{acc}(\mathcal{F}_1) > \text{acc}(\mathcal{F}_2)$, then $\mathcal{F}_1 > \mathcal{F}_2$;
 - (iii) If $\text{acc}(\mathcal{F}_1) = \text{acc}(\mathcal{F}_2)$, then $\mathcal{F}_1 = \mathcal{F}_2$.

Definition 6. Let $\mathcal{F} = (\alpha_F, \beta_F)$, $\mathcal{F}_1 = (\alpha_{F_1}, \beta_{F_1})$ and $\mathcal{F}_2 = (\alpha_{F_2}, \beta_{F_2})$ be three FFSs and $\lambda > 0$, then their operations are defined as follows:

- (1) $\mathcal{F}_1 \oplus \mathcal{F}_2 = \left(\left(\alpha_{F_1}^3 + \alpha_{F_2}^3 - \alpha_{F_1}^3 \alpha_{F_2}^3 \right)^{\frac{1}{3}}, \beta_{F_1} \beta_{F_2} \right)$.
- (2) $\mathcal{F}_1 \otimes \mathcal{F}_2 = \left(\alpha_{F_1} \alpha_{F_2}, \left(\beta_{F_1}^3 + \beta_{F_2}^3 - \beta_{F_1}^3 \beta_{F_2}^3 \right)^{\frac{1}{3}} \right)$.
- (3) $\mathcal{F}^k = \left(\alpha_F^k, \left(1 - (1 - \beta_F^3)^k \right)^{\frac{1}{3}} \right)$.
- (4) $k\mathcal{F} = \left(\left(1 - (1 - \alpha_F^3)^k \right)^{\frac{1}{3}}, \beta_F^k \right)$.

Definition 7. Let $\mathcal{F}_1 = (\alpha_{F_1}, \beta_{F_1})$ and $\mathcal{F}_2 = (\alpha_{F_2}, \beta_{F_2})$ be two FFSs. Then the Euclidean distance between $\mathcal{F}_1$ and $\mathcal{F}_2$ is:

$$d(\mathcal{F}_1, \mathcal{F}_2) = \sqrt{\frac{1}{2} [(\alpha_{F_1}^3 - \alpha_{F_2}^3)^2 + (\beta_{F_1}^3 - \beta_{F_2}^3)^2 + (\pi_{F_1}^3 - \pi_{F_2}^3)^2]}. \quad (6)$$

4. Methodology

This section presents an integrated Fermatean fuzzy SWARA and TOPSIS method for the sustainable packaging selection problem in logistics. This methodology is selected for various reasons related to the structure of the considered problem. Firstly, FFNs provide a highly effective framework for modelling the uncertainty and vagueness inherent in sustainable packaging decision-making problems. The evaluation of sustainable packaging alternatives typically involves qualitative and conflicting criteria—such as environmental impact, economic feasibility, recyclability, regulatory compliance, and social acceptance—assessed by experts whose judgments may be imprecise or linguistically expressed. Unlike traditional fuzzy sets and intuitionistic fuzzy sets, Fermatean fuzzy sets allow a wider domain for membership and non-membership degrees, enabling decision-makers to represent higher levels of uncertainty and hesitation more flexibly [24]. This enhanced expressive capacity makes FFNs particularly suitable for sustainability-related problems, where incomplete information, subjective assessments, and ambiguity are unavoidable. Consequently, the use of Fermatean fuzzy numbers improves the robustness and reliability of the evaluation process in the sustainable packaging selection problem.

Secondly, the SWARA method offers several advantages compared to other weighting approaches such as AHP, entropy, or CRITIC. SWARA enables experts to determine criteria weights in a structured yet cognitively intuitive manner by sequentially assessing the relative importance of criteria [57]. This step-wise procedure reduces computational complexity and avoids the need for extensive pairwise comparisons, thereby minimizing inconsistency issues commonly observed in methods such as AHP [58]. Furthermore, SWARA effectively incorporates expert knowledge and domain-specific insights, which is particularly valuable in sustainability contexts where subjective expertise plays a central role. Its transparency, flexibility, and relatively simple implementation [59] make SWARA a reliable and efficient tool for deriving criteria weights in sustainable packaging evaluation problems.

Thirdly, TOPSIS possesses significant strengths compared to other MCDM ranking methods such as VIKOR, ELECTRE, or SAW. The fundamental principle of TOPSIS is to select the alternative closest to the positive ideal solution and farthest from the negative ideal solution and to provide a clear and rational decision logic [60]. Unlike some outranking methods that may produce partial rankings or ambiguous dominance relations, TOPSIS generates a complete and easily interpretable ranking of alternatives. Additionally, TOPSIS simultaneously considers both benefit and cost criteria while preserving the relative performance differences among alternatives [61]. Its computational efficiency, conceptual clarity, and compatibility with various fuzzy environments further enhance its applicability. In the context of sustainable packaging selection, TOPSIS ensures a balanced and comprehensive evaluation by integrating multiple environmental, economic, and technical criteria into a single performance index.

In summary, the considered FF-SWARA-TOPSIS methodology is a powerful tool for practitioners to solve the sustainable packaging selection problem under an uncertain environment while considering several criteria. The proposed method evaluates the expertise level of decision-makers, determines criteria weights, and ranks alternatives. The detailed procedure for the proposed method is outlined below.

4.1. Stage 1: Evaluating Expertise Level of Decision-Makers

Step 1: Firstly, the experts are evaluated, and the corresponding weights (or reputational scores) are determined in accordance with Equation (7).

$$\psi_t = \frac{S^+(E_t)}{\sum_{t=1}^d S^+(E_t)} = \frac{1 + \mu_t^3 - \nu_t^3}{\sum_{t=1}^d (1 + \mu_t^3 - \nu_t^3)} \quad (7)$$

Step 2: In this stage, the opinions of the experts are collected and transformed into a decision matrix based on the linguistic variables specified in Table 3. Each expert evaluates every criterion using the linguistic scale presented in Table 4. Subsequently, the assessment of criterion j by expert t is expressed in terms of a Fermatean fuzzy number. The evaluation of criterion j by expert t can be represented as $A_{jt} = (\mu_{jt}, \nu_{jt})$, where μ_{jt} denotes the membership degree, and ν_{jt} represents the non-membership degree.

Table 3. Linguistic terms for expert evaluation.

Linguistic Term	μ	ν
Absolutely Skilled (AS)	0.9	0.1
Very Skilled (VS)	0.7	0.3
More Skilled (MS)	0.5	0.5
Skilled (S)	0.3	0.7
Less Skilled (LS)	0.1	0.9

Table 4. Linguistic terms for criteria evaluation.

Linguistic Term	μ	ν
Extremely Important (EI)	0.9	0.1
Very Important (VI)	0.7	0.3
Important (I)	0.5	0.5
Less Important (LI)	0.3	0.7
Extremely Unimportant (EU)	0.1	0.9

Step 3: The opinions of experts considering criteria aggregated in Step 3 to construct a Fermatean fuzzy decision matrix. This aggregation process incorporates each expert weight (ψ_t) and experts assigned higher weights contribute more substantially to the overall outcome. This step aims to combine each expert's evaluation into a unified overall assessment for each criterion.

$$z_j = Y(\mu_j, \nu_j) = \left(\prod_{t=1}^d (\mu_{jt})^{\psi_t}, \sqrt[3]{1 - \prod_{t=1}^d (1 - (\nu_{jt})^3)^{\psi_t}} \right), j = 1, \dots, n \quad (8)$$

z_j denotes the aggregated value for each criterion j , and n represents criteria in total.

Step 4: Calculate the positive score $S^+(j)$

$$S^+(j) = 1 + \mu_j^3 - \nu_j^3 \quad (9)$$

4.2. Stage 2: Determining Criteria Weights

Step 5: Rank the criteria based on their calculated positive scores. The ranking is performed in descending order, with the criterion having the highest score placed at the top of the list and the criterion with the lowest score at the bottom.

Step 6: Differ the positive score of the second-ranked criterion $S^+(j-1)$ from the positive score $S^+(j)$ to calculate the comparative significance C_j .

Step 7: Calculate the comparative coefficients.

$$k_j = \begin{cases} 1, & j = 1 \\ c_j + 1, & j > 1 \end{cases} \quad (10)$$

Step 8: Determine recalculated weights.

$$q_j = \begin{cases} 1, & j = 1 \\ \frac{q_{j-1}}{k_j}, & j > 1 \end{cases} \quad (11)$$

Step 9: Normalize the recalculated weights to calculate final weights.

$$w_j = \frac{q_j}{\sum_{j=1}^n q_j} \quad (12)$$

4.3. Stage 3: Ranking Alternatives

Step 10: Construct the decision matrix by collecting expert opinions regarding each criterion. $A_{tij} = (\mu_{tij}, \nu_{tij})$ represents that each expert evaluates each alternative considering each criterion. m and n indicate alternatives and criteria.

Step 11: Form a decision matrix by using aggregated opinions.

$$Z = \begin{bmatrix} (\mu_{11}, \nu_{11}) & (\mu_{12}, \nu_{12}) & \cdots & (\mu_{1n}, \nu_{1n}) \\ (\mu_{21}, \nu_{21}) & \ddots & \ddots & (\mu_{2n}, \nu_{2n}) \\ \vdots & \ddots & \ddots & \vdots \\ (\mu_{m1}, \nu_{m1}) & \cdots & \cdots & (\mu_{mn}, \nu_{mn}) \end{bmatrix} \quad (13)$$

$$z_{ij} = Z(\mu_{ij}, \nu_{ij}) = \left(\sqrt{1 - \prod_{t=1}^d (1 - (\mu_{ij}^t)^3)^{\psi^t}}, \prod_{t=1}^d (\nu_{ij}^t)^{\psi^t} \right) \quad (14)$$

Step 12: Use score functions to determine Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS).

$$S^+ = \begin{cases} \max_i \langle \text{score}(z_{ij}) \rangle | j = 1, 2, \dots, n; \text{ benefits} \\ \min_i \langle \text{score}(z_{ij}) \rangle | j = 1, 2, \dots, n; \text{ costs} \end{cases} \quad (15)$$

$$S^+ = \{(\mu_1^+, \nu_1^+), (\mu_2^+, \nu_2^+), \dots, (\mu_n^+, \nu_n^+)\} \quad (16)$$

$$S^- = \begin{cases} \min_i \langle \text{score}(z_{ij}) \rangle | j = 1, 2, \dots, n; \text{ benefits} \\ \max_i \langle \text{score}(z_{ij}) \rangle | j = 1, 2, \dots, n; \text{ costs} \end{cases} \quad (17)$$

$$S^- = \{(\mu_1^-, \nu_1^-), (\mu_2^-, \nu_2^-), \dots, (\mu_n^-, \nu_n^-)\} \quad (18)$$

Step 13: The weighted Euclidean distances are calculated for alternatives.

$$D(S_i, S^+) = \sum_{j=1}^n w_j \sqrt{\frac{1}{2} \left[\left(\mu_{ij}^3 - (\mu_j^+)^3 \right)^2 + \left(\nu_{ij}^3 - (\nu_j^+)^3 \right)^2 + \left(\pi_{ij}^3 - (\pi_j^+)^3 \right)^2 \right]} \quad (19)$$

$$D(S_i, S^-) = \sum_{j=1}^n w_j \sqrt{\frac{1}{2} \left[\left(\mu_{ij}^3 - (\mu_j^-)^3 \right)^2 + \left(\nu_{ij}^3 - (\nu_j^-)^3 \right)^2 + \left(\pi_{ij}^3 - (\pi_j^-)^3 \right)^2 \right]} \quad (20)$$

Step 14: Determine closeness coefficients.

$$\phi_j = \frac{D(S_i, S^-)}{D(S_i, S^-) + D(S_i, S^+)} \quad (21)$$

Step 15: In the final step, the alternatives are ranked in descending order based on their closeness coefficients. The alternative with the highest coefficient is identified as the optimal choice.

5. Sustainable Packaging Selection Problem

5.1. Description of Experts

The experts participating in the study consist of industry professionals from companies engaged in sustainable packaging practices, along with academic scholars whose research and expertise focus specifically on sustainable packaging. Table 5 provides information about experts in detail. There are a total of 10 experts involved in the study from a variety of different disciplines and levels of education. Respondent's ages ranged from 30 to 50, indicating that most respondents are people who are in the middle stage of their careers. In terms of education, this group is quite highly educated. Four of the respondents hold a bachelor's degree, two respondents hold a master's degree, three respondents have a doctorate and one person has an associate's degree. Given the fact that there are three PhD holders, there is adequate mixing between practical experience from industry and academic expertise in the sample. Participants represent a variety of jobs such as manager, export specialist, business owner, board member and academics. This diversity among participants affords more managerial and strategic insight in the study.

Table 5. The information about experts.

Expert No	Education Level	Position	Experience
Expert 1 (E_1)	Bachelor	Manager	8
Expert 2 (E_2)	Bachelor	Export specialist	1
Expert 3 (E_3)	Ph.D.	Academic	15
Expert 4 (E_4)	Ph.D.	Board member	1
Expert 5 (E_5)	Bachelor	Export specialist	7
Expert 6 (E_6)	Ph.D.	Academic	16
Expert 7 (E_7)	Bachelor	Manager	16
Expert 8 (E_8)	M.Sc.	Business owner	3
Expert 9 (E_9)	M.Sc.	Manager	5
Expert 10 (E_{10})	Associate degree	Manager	3

Participants' professional experience ranges from 1 year to 16 years in their current positions. This indicates a good amount of experience specific to the roles they hold. Overall, the sample reflects a combination of managerial experience, advanced educational background, and varying degrees of institutional involvement in sustainable packaging practices, thereby providing a multifaceted expert perspective for the academic study.

5.2. Sustainable Packaging Alternatives

Packaging plays a significant role in the transportation of products to customers. Furthermore, sustainable packaging is an important tool in decreasing the number of plastics and other non-biodegradable materials in logistics operations. Recycled, biodegradable, and compostable materials have been commonly used in sustainable packaging alternatives for logistics operations. After a comprehensive investigation of the related industry, recycled cardboard, recycled plastic, biodegradable plastic, and compostable plastic have been considered for the selection problem.

- Recycled cardboard (A_1): Cardboard is among the most extensively recyclable materials globally, due to its paper-based composition, which facilitates efficient recycling processes. Recycling cardboard plays a crucial role in mitigating solid waste accumulation, lessening the demand for natural resources, and decreasing the volume of waste directed to landfills. This characteristic contributes to reduced energy con-

sumption and diminishes the dependence on raw materials, such as timber, thereby supporting environmental sustainability. Additionally, it contributes to improved air quality by reducing the environmental impact associated with waste disposal and resource extraction.

- Recycled plastic (A_2): Many packaging materials are composed of plastics; while not all types of plastic are recyclable, polyethylene terephthalate (PET) is an exception. As a lightweight material, PET can be effectively recycled and subsequently repurposed into a wide range of everyday products.
- Biodegradable plastic (A_3): Biodegradable plastic materials can be decomposed by living microorganisms. While certain bioplastics, such as those derived from corn starch, sugar cane, and wheat, may compete with human food resources, there are alternative bioplastics, including microbial polyesters known as polyhydroxyalkanoates (PHA), which do not rely on food crops. Biodegradable plastics play a significant role in minimizing waste and alleviating pressure on landfills, thereby supporting the principles of a circular economy by promoting the reuse and regeneration of materials.
- Compostable plastic (A_4): Compostable plastics, a subset of biodegradable plastics, generally require industrial composting facilities for decomposition. However, they must first be properly collected to ensure they undergo the appropriate composting process. Compostable plastics may be made from biological resources or fossil raw materials.

5.3. Criteria for Sustainable Packaging Selection

First, criteria with a comprehensive literature review on the related topic have been examined. Then, experts have been consulted to determine suitable criteria for the considered problem. Finally, the common and suggested criteria that have the potential to affect the sustainable packaging selection process have been selected. Here, technology level (C_2), material specification (C_3), reusability (C_4), environmental impact (C_5), physical attributes (C_6), and loading capacity (C_7) are considered as benefit criteria. Only production cost (C_1) is a cost criterion. Table 6 summarizes criteria specifications used in the sustainable packaging selection problem.

Table 6. The criteria to evaluate the sustainable packaging selection problem.

Code	Criteria	Type	Source
C_1	Production cost	Cost	[19,33]
C_2	Technology level	Benefit	[62,63]
C_3	Material specification	Benefit	[64]
C_4	Reusability	Benefit	[63]
C_5	Environmental impact	Benefit	[19,64]
C_6	Physical attributes	Benefit	[65,66]
C_7	Loading capacity	Benefit	[67]

Production cost is an important factor when considering sustainable packaging alternatives. Some materials have higher production costs due to their nature. For instance, bioplastics are more expensive than conventional plastics or recycled plastics because the cost of bio-based raw materials is higher. Technology level means integrating new or advanced technology in production processes to get eco-friendly packages. Material specification focuses on sustainable materials (e.g., recycled or compostable) to reduce waste. Reusability means how a package can be reused after a product sale. Environmental impact concerns how a package affects the environment after the usage period. Physical attributes are visual-related specifications such as shape, durability, protection level, and the weight of the package. Loading capacity determines how many products or weights the package can handle.

5.4. Evaluation of Sustainable Packaging Alternatives with FF-SWARA-TOPSIS

The MCDM model aims to evaluate the experts, which is a crucial aspect of the decision-making process. This step is essential because the experts' opinions will be crucial in determining the final weights for each of the performance metrics in the model. Education level, the position of the expert, and the experience of experts have been considered in the evaluation process. These factors have expressed in numerical term in Table 7. These numerical terms have been converted into FFNs by using Table 3.

Table 7. Expert specifications.

Expert	Education	Position	Experience
E_1	4	5	5
E_2	4	4	3
E_3	5	4	4
E_4	5	5	5
E_5	4	4	4
E_6	5	5	5
E_7	3	5	5
E_8	4	5	3
E_9	4	5	3
E_{10}	3	5	3

The rankings are crucial to evaluate experts, and these evaluations are subsequently incorporated into the final calculations for the criteria as weights. By assigning appropriate weights based on the expert rankings, the model ensures that the opinions of more reputable experts carry greater influence, thereby enhancing the accuracy and reliability of the decision-making process. Rankings of experts have been calculated by using Equation (7). Three experts have been deemed “absolutely skilled (AS)”, and the rest are “very skilled”. The final score for each expert is E_4 – E_6 : 0.116, E_1 – E_7 : 0.106, E_3 – E_8 : 0.098, E_5 – E_9 : 0.091, and E_2 – E_{10} : 0.087, respectively.

In step 2, expert opinions have been gathered and converted into a decision matrix. Table 8 presents expert evaluations for criteria. Linguistic terms are subsequently converted into FFNs using the conversion guidelines outlined in Table 4. In step 3, the evaluations provided by the experts are then aggregated using Equation (8), as presented in Table 9.

Table 8. Criteria evaluations by each expert.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
E_1	VI	VI	VI	VI	EI	VI	VI
E_2	LI	VI	VI	VI	VI	I	I
E_3	VI	I	I	I	I	LI	VI
E_4	I	I	LI	I	VI	LI	LI
E_5	I	I	I	I	I	I	I
E_6	I	I	I	I	I	I	LI
E_7	I	I	I	I	I	I	VI
E_8	VI	EI	EI	VI	VI	VI	VI
E_9	VI	EI	EI	EI	EI	VI	EI
E_{10}	EI	EI	EI	EI	EI	VI	EI

Table 9. Aggregated criteria evaluations.

Criteria	μ	ν
C_1	0.57	0.54
C_2	0.63	0.51
C_3	0.59	0.54
C_4	0.61	0.51
C_5	0.65	0.49
C_6	0.51	0.58
C_7	0.57	0.46

In Step 4, the score values of the criteria are computed using Equation (9), based on the aggregated criterion evaluations presented in Table 9. Each criterion has been ordered related to score values in descending order in Step 5. Steps 6–9 of FF-SWARA are then applied to determine the weight of each criterion as given in Table 10.

Table 10. Results of FF-SWARA for criteria.

Criteria	Score	c_j	k_j	q_j	Weight
C_5	1.160	0.000	1.000	1.000	0.156
C_2	1.116	0.043	1.043	0.958	0.149
C_4	1.096	0.020	1.020	0.940	0.146
C_7	1.090	0.006	1.006	0.934	0.146
C_3	1.048	0.043	1.043	0.896	0.140
C_1	1.034	0.014	1.014	0.883	0.138
C_6	0.936	0.098	1.098	0.805	0.125

After determining the criteria weights, a decision matrix has been constructed to evaluate sustainable packaging alternatives based on linguistic terms presented in Table 4 in Step 10. Then, experts' opinions have been aggregated with Equation (14) in Step 11. In Step 12, the positive and negative ideal solutions have been determined by Equations (15)–(18) and provided in Table 11.

Table 11. Positive and negative ideal solutions.

Criteria	Positive Ideal Solution		Negative Ideal Solution	
	μ	ν	μ	ν
C_1	0.715	0.308	0.816	0.188
C_2	0.807	0.202	0.663	0.371
C_3	0.816	0.188	0.696	0.347
C_4	0.859	0.140	0.782	0.246
C_5	0.847	0.149	0.819	0.197
C_6	0.775	0.243	0.716	0.312
C_7	0.750	0.264	0.867	0.128

The weighted distances from the PIS and NIS are determined for each sustainable packaging option in Step 13. The positive–negative distances are given in Table 12. The closeness coefficient for each alternative is calculated by (21) in Step 14 and presented in Table 12. All alternatives are ranked in descending order related to closeness coefficients.

Table 12. Results of TOPSIS.

Alternatives	$D(S_i, S^+)$	$D(S_i, S^-)$	Closeness Coefficient
A_1	0.363	0.218	0.375
A_2	0.293	0.375	0.561
A_3	0.267	0.335	0.556
A_4	0.316	0.333	0.513

The final ranking of the alternatives is $A_2 > A_3 > A_4 > A_1$, respectively. The results show that recycled plastic is the most suitable option for sustainable packaging in logistics operations.

5.5. Sensitivity Analysis

Since the outcomes of MCDM methods are determined by weights assigned to the evaluation criteria, even minor variations in weight coefficients may lead to substantial changes in the ranking of alternatives. Therefore, conducting a sensitivity analysis is

essential to assess the robustness and reliability of the results. This section provides eight different scenarios based on differentiated weight coefficients. Scenario 1 assumes that each criterion has equally important weight. Scenarios 2–8 consider only one criteria with the highest weight, and other criteria have equal weight coefficients from criterion 1 to criterion 7. Table 13 presents weights that are employed in each scenario.

Table 13. Scenarios in the sensitivity analysis.

Scenario	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇
1	0.142	0.142	0.142	0.142	0.142	0.142	0.142
2	0.4	0.1	0.1	0.1	0.1	0.1	0.1
3	0.1	0.4	0.1	0.1	0.1	0.1	0.1
4	0.1	0.1	0.4	0.1	0.1	0.1	0.1
5	0.1	0.1	0.1	0.4	0.1	0.1	0.1
6	0.1	0.1	0.1	0.1	0.4	0.1	0.1
7	0.1	0.1	0.1	0.1	0.1	0.4	0.1
8	0.1	0.1	0.1	0.1	0.1	0.1	0.4

Table 14 reports the rankings of the alternatives under eight different weighting scenarios (S1–S8). The results shows that (A_2) predominantly attains the first position (S1–S7) and only slightly decreases to third place in Scenario 8. This indicates that (A_2) demonstrates a high level of robustness and remains the most favorable alternative under nearly all weighting configurations. Similarly, (A_3) generally ranks second (S1–S6), with minor fluctuations in Scenario 7 and Scenario 8, suggesting that its performance is relatively stable. In contrast, (A_4) consistently occupies middle positions (mostly third), while (A_1) remains ranked fourth (worst) across all scenarios. The complete stability of (A_1)’s position indicates that it is consistently the least preferred alternative regardless of changes in criterion weights.

Furthermore, no rank reversal occurs for the best and worst alternatives. The only observable changes take place between intermediate positions in Scenario 7 and Scenario 8, and these shifts are limited in magnitude. Therefore, the sensitivity analysis confirms that the overall ranking structure, particularly the identification of the best (A_2) and worst (A_1) alternatives, is highly robust to variations in weight coefficients. This stability enhances the reliability and credibility of the decision-making results derived from the applied weighting scheme.

Table 14. Results of the sensitivity analysis.

Alternatives	S1	S2	S3	S4	S5	S6	S7	S8
A_1	4	4	4	4	4	4	4	4
A_2	1	1	1	1	1	1	1	3
A_3	2	2	2	2	2	2	3	1
A_4	3	3	3	3	3	3	2	2

5.6. Comparative Analysis

This section provides a systematic comparison of the FF-SWARA-TOPSIS approach with other MCDM techniques. Table 15 presents MCDM techniques and a description of the differences among these techniques. These methods were deliberately selected to highlight the relative importance of three fundamental components of decision modeling: uncertainty representation, weighting strategy, and ranking mechanism.

First, crisp TOPSIS and triangular fuzzy TOPSIS were included to demonstrate the significance of considering uncertainty. While crisp TOPSIS operates under deterministic assumptions and ignores ambiguity in decision data, triangular fuzzy TOPSIS incorporates vagueness through conventional fuzzy numbers. By extending this structure to Fermatean fuzzy numbers, the proposed method benefits from a wider and more flexible uncertainty

domain, allowing simultaneous and more expressive modeling of membership and non-membership degrees. Second, FF-CRITIC-TOPSIS and FF-Entropy-TOPSIS were considered to emphasize the critical role of weighting strategies. Both methods determine criteria weights objectively based on data dispersion and information content. In contrast, FF-SWARA-TOPSIS relies on the SWARA method, which integrates expert judgment into the weighting process. Comparing these approaches makes it possible to evaluate how expert-driven and data-driven weighting mechanisms influence ranking stability and decision outcomes. Finally, FF-SWARA-SAW and FF-SWARA-VIKOR were selected to isolate and examine differences in ranking logic. Although these methods share the same Fermatean fuzzy environment and SWARA-based weighting structure, they apply distinct aggregation principles—additive (SAW), compromise-based (VIKOR), and distance-to-ideal (TOPSIS). This comparison enables a clear assessment of how the ranking mechanism itself affects the prioritization of alternatives.

Table 15. Description of the differences among MCDM techniques.

Method	Data Type	Uncertainty	Weighting	Amount of Uncertainty
Crisp TOPSIS	Crisp	No	Subjective	None
Triangular Fuzzy TOPSIS	TFN	Yes	Subjective	Moderate
Fermatean-CRITIC-TOPSIS	FFN	Yes	Objective	High
Fermatean-Entropy-TOPSIS	FFN	Yes	Objective	High
Fermatean-SWARA-SAW	FFN	Yes	Subjective	High
Fermatean-SWARA-VIKOR	FFN	Yes	Subjective	High
Fermatean-SWARA-TOPSIS	FFN	Yes	Subjective	High

Table 16 presents ranking orders related with each MCDM technique. According to the results, the ranking of alternatives in the considered method is totally different from the other techniques. This result shows that adjustments in uncertainty representation, weighting strategy, and ranking mechanism directly affect the ranking order. Furthermore, a correlation test has been conducted to validate the robustness and methodological contribution of the proposed FF-SWARA-TOPSIS approach.

Table 16. Comparative results.

Method	Ranking Order
Crisp TOPSIS	$A_1 > A_2 > A_3 > A_4$
Triangular-Fuzzy TOPSIS	$A_1 > A_3 > A_2 > A_4$
FF-CRITIC-TOPSIS	$A_4 > A_3 > A_2 > A_1$
FF-Entropy-TOPSIS	$A_4 > A_3 > A_2 > A_1$
FF-SWARA-SAW	$A_1 > A_2 > A_4 > A_3$
FF-SWARA-VIKOR	$A_2 > A_4 > A_1 > A_3$
FF-SWARA-TOPSIS *	$A_2 > A_3 > A_4 > A_1$

* The considered method in the study.

The correlation test provides noteworthy results about the comparison process in Table 17. The correlation between the considered method and crisp TOPSIS is weak and negative, indicating that it does not replicate deterministic ranking behavior. Its relationship with Triangular Fuzzy TOPSIS is moderately negative, suggesting that extending uncertainty modeling from triangular to Fermatean fuzzy sets meaningfully changes the decision outcomes. Compared with FF-CRITIC-TOPSIS and FF-Entropy-TOPSIS, the correlations are relatively low, implying that the weighting mechanism significantly influences ranking divergence. Its correlation with FF-SWARA-SAW is moderately positive, reflecting partial alignment due to the shared SWARA weighting structure. Finally, the negative correlation with FF-SWARA-VIKOR suggests that even when the weighting method is identical, the aggregation logic (distance-based TOPSIS vs. compromise-based VIKOR) substantially affects the final ranking.

Table 17. Results of the correlation test among MCDM methods.

	Crisp TOPSIS	TF-TOPSIS	FF-CRITIC-TOPSIS	FF-Entropy-TOPSIS	FF-SWARA-SAW	FF-SWARA-VIKOR	FF-SWARA-TOPSIS
Crisp TOPSIS	1	0.8	−1	−1	0.8	0	−0.2
TF-TOPSIS		1	−0.8	−0.8	0.4	0.6	−0.4
FF-CRITIC-TOPSIS			1	1	−0.8	0	0.2
FF-Entropy-TOPSIS				1	−0.8	0	0.2
FF-SWARA-SAW					1	−0.4	0.4
FF-SWARA-VIKOR						1	−0.4
FF-SWARA-TOPSIS							1

6. Discussion

This study suggests several critical managerial implications for decision makers in logistics and supply chain operations striving for sustainability. First, the selection of recycled plastic as the most suitable sustainable packaging alternative underlines the importance of aligning packaging decisions with broader environmental objectives, such as minimizing packaging-related waste. As supported by Varvzinskas & Markevi [68], the minimization of waste is a crucial aspect of eco-friendly packages. Furthermore, Ganesan [69] conclude that recycled plastics used in manufacturing processes generally exhibit a lower carbon footprint and reduced energy consumption compared to virgin plastics.

On the other hand, consumers perceive recycled plastics used in packaging (especially in the food sector) as more contaminated than virgin plastics [70]. Recycling companies should establish clear and transparent communication strategies to inform consumers about the benefits of recycled plastics and to reassure them that the use of recycled materials does not compromise product quality [71]. Advertisements and digital platforms play a crucial role in disseminating information about how recycled plastic packaging is produced and prepared prior to use. The design of recycled plastic packaging also plays an important role for many products to get competitive advantages over rival products. Managers should consider various eco-design options that distinguish recycled packaging from conventional alternatives while preserving aesthetic appeal and functional performance.

Policy makers or governments should also take responsibility to decrease the amount of raw plastic usage in package manufacturing processes. Governments can provide direct financial incentives to firms engaged in the production of recycled plastics. These may include tax credits, reduced value-added tax (VAT) rates for recycled-content products, investment subsidies for recycling infrastructure, and low-interest green financing schemes. In addition, public procurement policies can be strategically designed to create stable demand for recycled materials by mandating minimum recycled-content requirements in publicly funded projects. Extended Producer Responsibility (EPR) schemes require manufacturers to bear the financial and organizational responsibility for the end-of-life management of their products. Governments regulate the amount of raw plastic usage by economic interventions (e.g., green dot fee and packaging taxes) and direct interventions (recycled content standards and recycling targets) [72]. Finally, public awareness campaigns and educational initiatives are indispensable components of a comprehensive strategy. By promoting responsible consumption patterns and waste segregation practices, governments can improve the quality and quantity of recyclable materials entering the system. This, in turn, enhances the efficiency and economic viability of recycling operations.

Second, the results reveal that criteria such as environmental impact, technology level, and reusability significantly influence the decision-making process due to top three weight scores, suggesting that packaging decisions should not be made solely based on cost considerations. The negative environmental impact of packages can be alleviated by ensuring a longer circulation period with recycling processes. Recycling technologies, such as mechanical, chemical, and thermochemical, can provide support to reduce plastic package-based

waste [73]. The implementation of deposit-return schemes, the establishment of qualitative and quantitative targets, the use of economic incentives, and regulatory mandates may lead companies to use reusable materials in packaging production.

Finally, the integration of Fermatean fuzzy sets within the SWARA-TOPSIS framework provides managers in packaging industry with a robust tool to handle uncertainty and imprecise data, allowing for more reliable decision making in complex environments. This methodological approach enables managers to prioritize sustainable practices confidently without compromising operational efficiency, to improve their strategic alignment with the Sustainable Development Goals of the United Nations (particularly SDG 12), and to promote long-term value creation through responsible consumption and production practices.

7. Conclusions

This study employs an integrated MCDM framework to address the sustainable packaging selection problem in logistics operations under uncertainty. The considered FF-SWARA-TOPSIS methodology enables the systematic incorporation of expert judgments, the determination of criteria weights through a structured subjective weighting procedure, and the ranking of alternatives based on their relative closeness to ideal solutions. By employing Fermatean fuzzy numbers, the model effectively captures the ambiguity, hesitation, and imprecision inherent in sustainability-related decision-making contexts.

The empirical application of the model to four sustainable packaging alternatives (recycled cardboard, recycled plastic, biodegradable plastic, and compostable plastic) demonstrates the practical applicability and robustness of the proposed approach. The findings indicate that recycled plastic emerges as the most suitable alternative for logistics operations, followed by biodegradable plastic, compostable plastic, and recycled cardboard. Among the evaluated criteria, environmental impact, technology level, and reusability exert the most significant influence on the decision-making process, highlighting that sustainable packaging selection should extend beyond mere cost considerations and incorporate broader environmental and operational dimensions.

The sensitivity analysis confirms the stability of the ranking results, particularly with respect to the best and worst alternatives, thereby reinforcing the reliability of the proposed weighting and ranking structure. Furthermore, the comparative analysis with alternative MCDM techniques reveals that variations in uncertainty representation, weighting strategies, and aggregation logic substantially affect ranking outcomes.

From a managerial perspective, the proposed framework offers a practical decision-support tool for logistics and packaging managers seeking to align operational practices with sustainability objectives. By systematically evaluating multiple environmental, technical, and economic criteria, organizations can make more informed and transparent packaging decisions that contribute to waste reduction, resource efficiency, and long-term value creation. In addition, the model provides policymakers with analytical support for designing regulatory and incentive mechanisms that encourage the adoption of sustainable packaging solutions.

Scientifically, this study contributes to the literature by employing an MCDM methodology, thereby extending uncertainty modeling capacity in sustainable packaging selection problems. Unlike conventional crisp or traditional fuzzy approaches, the proposed methodology enables a more flexible and expressive representation of expert hesitation, enhancing the robustness and reliability of decision outcomes. Socially, the research supports the transition toward more responsible production and consumption patterns by guiding companies in selecting environmentally sustainable packaging alternatives. In doing so, it contributes to waste reduction, resource efficiency, and broader sustainability objectives aligned with global environmental priorities.

Despite its contributions, this study has certain limitations. The empirical application is based on a specific expert group and a limited number of packaging alternatives, which may restrict the generalizability of the findings. Future research may extend the proposed framework by incorporating additional criteria, expanding the alternative set, or applying interval-valued or hesitant Fermatean fuzzy environments.

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