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Multi-Criteria Evaluation of Circular E-Commerce Shipping Pack Alternatives under a Spherical Fuzzy Environment

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Abstract

This study presents a pure multi-criteria decision-making framework to select circular packaging alternatives for an e-commerce shipping pack that includes the outer box, void filler, sealing tape, and return handling. Packaging decisions in e-commerce are inherently multi-objective: they must protect products and reduce damage, keep total cost low, avoid dimensional-weight penalties, fit recovery infrastructure, and lower life-cycle emissions. These choices are often made with linguistic assessments, uncertain return rates, and heterogeneous customer behaviors across markets. To address this setting, we integrate Spherical Fuzzy Step-wise Weight Assessment Ratio Analysis (SF-SWARA) for criteria weighting and Spherical Fuzzy Combined Compromise Solution (SF-CoCoSo) for alternative ranking. A criteria system is defined to reflect operational and circularity priorities, including protective performance, total cost of ownership, compatibility with local collection and recycling systems, consumer acceptance and convenience, hygiene and contamination risk in returns, feasibility of implementing reverse logistics, and carbon footprint. An expert panel expresses relative importance and alternative performance using spherical fuzzy linguistic terms, and SF-SWARA yields a normalized weight vector. Five alternatives are assessed under the same spherical fuzzy environment: a single-use recyclable pack, a reusable pack, a compostable pack, a deposit-return pack, and a minimal-pack design. SF-CoCoSo generates compromise scores by combining additive and multiplicative principles, enabling balanced choices under conflicting objectives. Robustness is examined through sensitivity analysis that perturbs key weights and by benchmarking rankings against an alternative spherical fuzzy method. The framework provides a transparent, replicable decision aid for e-retailers, third-party logistics providers, and packaging designers, supporting context-specific adoption of circular packaging while safeguarding fulfillment performance and customer experience.

Keywords: circular packaging; e-commerce logistics; shipping pack selection; spherical fuzzy sets; CoCoSo; SWARA

1. Introduction

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The rapid expansion of e-commerce has transformed shipping packaging from a routine logistics component into a strategic sustainability issue. Escursell et al. [1] reviewed the evolution of e-commerce packaging and showed that the growth of online purchasing has been accompanied by rising packaging-related waste, oversizing, and environmental burdens. Silva and Pålsson [2] further argued that packaging should be evaluated not only as a material choice but also as a logistics system that affects supply-chain efficiency, circularity, and environmental performance. In parallel, sustainable packaging research has increasingly emphasized that packaging outcomes are shaped by interacting technological, organizational, and market factors rather than by single design variables alone [3].

In e-commerce settings, packaging decisions are particularly complex because the shipping pack must satisfy several conflicting objectives simultaneously. Rezaei et al. [4] demonstrated that sustainable product-package design is inherently a multi-criteria problem in which functional, economic, and environmental objectives must be balanced simultaneously. In online retail, this challenge becomes sharper because packaging is directly tied to product protection, void space, transport efficiency, dimensional-weight charges, and fulfillment operations. Lu et al. [5] showed that consumer reactions to overpackaging solutions are closely linked to perceived environmental benefits and practical usability, while Xie et al. [6] found that consumer preference for e-commerce packaging solutions is influenced by recycling systems, government support, and perceived participation value. Therefore, shipping-pack selection cannot be reduced to a single issue such as low material use or recyclability; rather, it requires the joint consideration of protection, cost, recovery feasibility, customer acceptance, and life-cycle performance [4–6].

The transition from linear packaging models to circular packaging systems adds another layer of complexity. Lai et al. [7] proposed that reusable packaging combined with reverse logistics can support more sustainable online shopping by extending packaging service life and enabling resource recovery. Nanayakkara et al. [8] also highlighted that e-commerce returns and reverse logistics should be embedded within broader circular-economy frameworks rather than treated as isolated after-sales activities. At the same time, recent literature shows that reusable or circular packaging systems do not automatically yield superior outcomes. Pålsson and Olsson [9] reviewed comparative studies on disposable and reusable packaging and concluded that sustainability outcomes vary substantially with system conditions, use intensity, and recovery design. Miao et al. [10] likewise showed that consumers' perceptions of reusable packaging are shaped by system design, convenience, and barriers encountered across different stages of use. From a behavioral and managerial perspective, deposit-refund or reward mechanisms may also affect return participation and circular performance in online retailing contexts [11].

Recent empirical studies have deepened this debate by showing that the environmental and operational performance of circular packaging depends strongly on contextual variables. Frommeyer et al. [12] assessed eco-friendly packaging in online retail through a multi-method perspective and emphasized the need to reconcile environmental evaluations with stakeholder expectations and implementation realities. González Romero et al. [13] demonstrated that the carbon performance of reusable e-commerce packaging is particularly sensitive to packaging material, return and reuse

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rate, and supply-chain design. Similarly, Park et al. [14] showed that the environmental outcomes of returnable packaging systems vary across e-commerce businesses and packaging-management models, indicating that business architecture and logistics configuration are decisive variables rather than secondary considerations. Ram et al. [15] further underlined that consumer behavioral intention remains a critical condition for the successful adoption of circular e-commerce packaging systems. Recent studies further confirm that circular and sustainable logistics decisions increasingly require integrated decision-support models rather than single-dimensional assessments. Tramarico et al. [16] developed a fuzzy multi-criteria decision-making (MCDM) framework for circular supply chains and emphasized that operational factors and external sustainability dimensions should be jointly considered when evaluating circular strategies. Similarly, Yüksel et al. [17] proposed an integrated fuzzy MCDM model for sustainable logistics performance in green supply chains, incorporating procurement logistics, production logistics, reverse logistics, distribution logistics, and disposal logistics. These studies are relevant to the present research because e-commerce shipping-pack selection is closely connected with reverse logistics, recovery infrastructure, distribution efficiency, and end-of-life management. However, while recent circular logistics studies provide broader supply-chain-level evaluation models, they do not specifically address circular e-commerce shipping packs as integrated configurations consisting of the outer package, void filler, sealing component, and return-related structure. Taken together, these studies suggest that the superiority of a packaging alternative cannot be assumed a priori; it must be evaluated within its specific operational, behavioral, and recovery context [12–15].

This context has made MCDM increasingly relevant for sustainable packaging research. Rezaei et al. [4] applied a multi-criteria life-cycle approach to product-package design, while Sun and Yang [18] used an Analytic Hierarchy Process (AHP) framework to evaluate reusable takeaway container design by integrating user and operational considerations. At the packaging-system level, Rajendran and Ranjitharamasamy [19] developed a fuzzy MCDM framework for selecting sustainable circular packaging models, and Belbag [20] proposed a Fermatean fuzzy Step-wise Weight Assessment Ratio Analysis (SWARA)-Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach for sustainable packaging selection in logistics operations. These studies confirm the suitability of MCDM methods for packaging problems characterized by conflicting criteria and qualitative judgments. Despite the growing body of research on sustainable and circular packaging, existing studies largely treat packaging decisions either at the material level or within isolated system components. However, real-world e-commerce packaging decisions are inherently system-level problems involving multiple interdependent elements such as outer packaging, cushioning materials, sealing mechanisms, and return logistics structures. This systemic perspective remains underexplored in the literature [4, 19, 20].

Although previous studies have made valuable contributions to sustainable packaging decision-making, the existing literature still shows a clear fragmentation in terms of problem focus and decision scope. For example, Gülsün and Mic [21] developed an integrated fuzzy MCDM model for sustainable green packaging material selection, while Mahajan et al. [22] proposed a hybrid MCDM framework for selecting biodegradable polymers for food packaging applications. More recent studies have

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extended fuzzy MCDM applications to green packaging supplier selection and circular-economy-oriented supplier evaluation in the packaging industry, as shown by Puška et al. [23] and Nguyen et al. [24] In parallel, Tenhunen-Lunkka et al. [25] emphasized that reusable packaging requires a circular business model perspective in which feasibility, desirability, viability, and sustainability should be jointly considered. These studies confirm the relevance of fuzzy MCDM, circular economy principles, and reusable packaging models for sustainable packaging decisions. However, they mainly focus on packaging materials, biodegradable polymers, suppliers, or reusable packaging business models, rather than on the integrated selection of e-commerce shipping pack systems. In contrast, the present study evaluates circular e-commerce shipping pack alternatives as system-level configurations that jointly include the outer package, void filler, sealing component, and return-related structure. Therefore, the contribution of this study lies not only in applying a spherical fuzzy MCDM model, but also in structuring circular e-commerce packaging selection as a system-level decision problem that integrates protection, cost, circularity, reverse logistics feasibility, customer experience, and environmental performance under uncertainty.

Accordingly, this study develops an integrated MCDM framework to evaluate circular e-commerce shipping-pack alternatives under uncertainty. The study treats shipping packs as system-level alternatives rather than isolated material options and assesses them through a comprehensive set of criteria covering protective and functional performance, economic and operational efficiency, circularity and end-of-life alignment, reverse logistics feasibility, customer and user experience, and environmental impact. Within this framework, Spherical Fuzzy SWARA (SF-SWARA) is used to determine criteria weights and Spherical Fuzzy CoCoSo is employed to rank alternative shipping-pack configurations. This study makes three primary contributions to the literature. First, it consolidates fragmented research streams on e-commerce packaging, circular economy, reverse logistics, and consumer behavior into a unified evaluation framework. Second, it conceptualizes shipping-pack alternatives as context-dependent circular systems rather than isolated material choices. Third, it incorporates expert uncertainty through a spherical fuzzy MCDM environment, thereby enhancing the robustness of decision-making under ambiguity. The resulting framework is intended to support e-retailers, packaging designers, and logistics decision-makers in selecting circular shipping-pack solutions that are not only environmentally preferable but also operationally feasible and market-compatible. This study contributes to the literature by addressing circular e-commerce packaging selection from a system-level perspective rather than reducing it to a single material choice. It evaluates shipping pack alternatives as integrated configurations that include outer packaging, filler, sealing components, and the return structure. Methodologically, the study combines Step-SWARA and Combined Compromise Solution (CoCoSo) within a spherical fuzzy environment to capture expert uncertainty and support robust multi-criteria evaluation. In doing so, it provides a structured and practical decision-support framework for selecting circular shipping-pack solutions that are both environmentally and operationally viable. The proposed methodology is presented in Figure 1.

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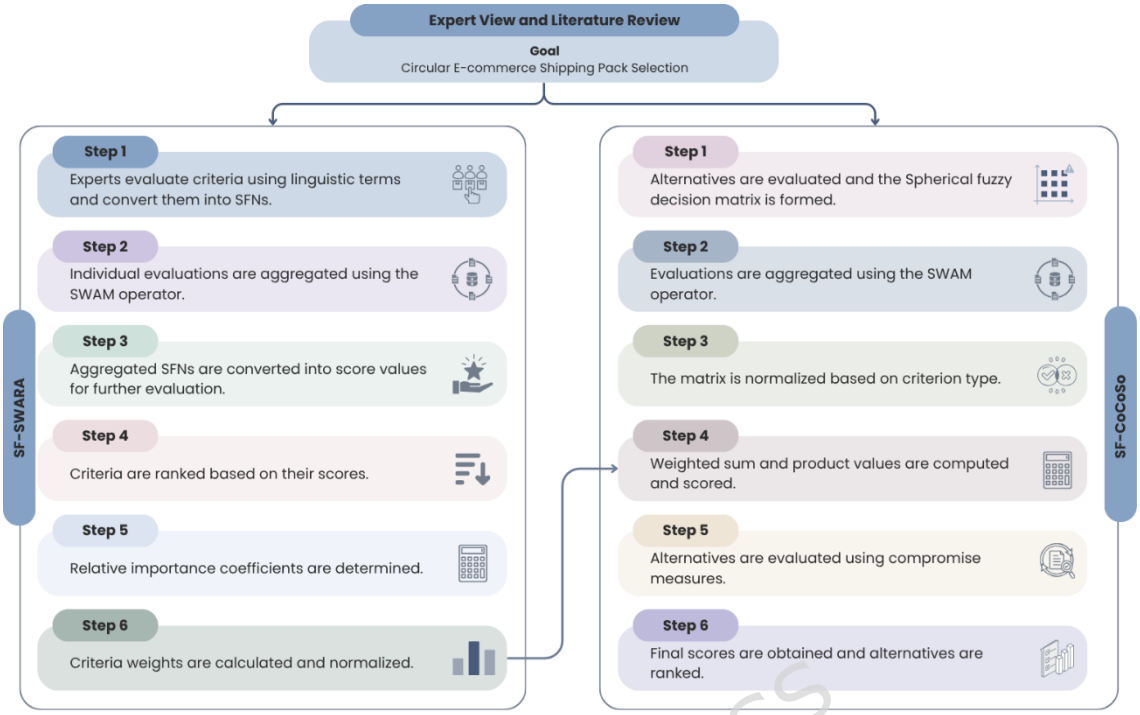


Figure 1. Proposed methodology

Recent methodological developments also show that CoCoSo and SWARA-based models have been increasingly extended under advanced uncertainty environments. Bonab and Yamchi [26] developed a spherical fuzzy FUCOM-CoCoSo model for prioritizing carbon-footprint reduction strategies, demonstrating the suitability of spherical fuzzy CoCoSo for sustainability-oriented decisions involving expert hesitation. Khan et al. [27] extended CoCoSo under circular non-linear Diophantine fuzzy sets and highlighted its ability to improve ranking stability and uncertainty handling. Other uncertainty-aware extensions have also been proposed. Lin et al. [28] integrated Z-numbers with ITARA and CoCoSo for sustainable order allocation, while Haseli et al. [29] developed a fuzzy ZE-number-based BCM-CoCoSo framework to incorporate both decision-maker judgments and expert reliability. Jiang et al. [30] further introduced a complex fuzzy Z-number-based SWARA-CoCoSo framework, showing how SWARA and CoCoSo can be combined under reliability-sensitive fuzzy information. These studies demonstrate the methodological flexibility of CoCoSo and SWARA-CoCoSo under different uncertainty extensions. Nevertheless, their applications mainly focus on ICT sustainability, cloud service provider selection, order allocation, urban transportation, or urban development assessment. In contrast, the present study applies SF-SWARA and SF-CoCoSo to the circular e-commerce shipping-pack selection problem, where expert hesitation, operational trade-offs, reverse logistics feasibility, and environmental performance must be evaluated simultaneously.

2. Materials and Methods

The evolution of fuzzy logic saw a significant transition when Atanassov [31] established Intuitionistic fuzzy sets (IFSs), which added non-membership and hesitancy functions to the traditional membership degree. To further expand the admissible

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membership space, Yager [32] later developed Pythagorean fuzzy sets (PFSs) by requiring the sum of the squares of these parameters to be within a unit interval. Building upon these mathematical foundations, Gündoğdu and Kahraman [33] introduced Spherical fuzzy sets (SFSs) as a more versatile generalization. This innovative framework defines membership, non-membership, and hesitancy as independent degrees, with their squared sums remaining less than or equal to 1.

SFS is specifically chosen for this study due to its superior capacity to model the multi-dimensional uncertainty found in modern e-commerce logistics. Unlike previous models, SFS allows experts to assign values to membership, non-membership and hesitancy independently on a spherical surface [33,34]. This geometric flexibility provides decision-makers with a larger preference domain and the freedom to express subjective judgments more accurately under ambiguous conditions [35]. By isolating the degree of hesitation as a separate parameter, the methodology effectively minimizes information loss and captures the nuances of expert uncertainty more comprehensively than classical fuzzy extensions [34].

The proposed methodology integrates SF-SWARA and SF-CoCoSo to select the most suitable circular packaging alternatives. In this framework, the SF-SWARA method is used to calculate the weights of the evaluation criteria. Subsequently, the SF-CoCoSo technique is applied to rank the alternatives based on the determined weights. This integrated pipeline identifies a compromise solution by balancing conflicting objectives, such as lowering total ownership costs while maximizing compatibility with local recycling infrastructure.

A Spherical Fuzzy Number (SFN) can be formally represented as follows [36]:

$$\tilde{S} = \{x,(\mu_{\tilde{S}}(x),\nu_{\tilde{S}}(x),\pi_{\tilde{S}}(x))\,|\,x \in X\} \quad (1)$$

$$\mu_{\tilde{S}}(x)^2 + \nu_{\tilde{S}}(x)^2 + \pi_{\tilde{S}}(x)^2 \leq 1 \quad (2)$$

Here, $\mu_{\tilde{S}}(x)$, $\nu_{\tilde{S}}(x)$ and $\pi_{\tilde{S}}(x)$ are degree of membership, degree of non-membership and degree of hesitation associated with the element x, respectively.

2.1. Weighting of criteria with SF-SWARA

The SWARA was originally established by Keršulienė et al. [37] to determine criteria weights based on professional judgment. This study utilizes the Spherical fuzzy extension of SWARA to better manage the uncertainty inherent in circular packaging decisions. The process begins with experts using linguistic scales to evaluate the relative importance of operational and environmental criteria [38]. These assessments are then converted into SFNs to independently capture membership, non-membership and hesitancy degrees [35]. Through a stepwise comparison mechanism, experts determine the significance of each criterion relative to the preceding one in the ranking. Finally, the model recalculates and normalizes these values to produce the definitive weights.

The SF-SWARA method is selected for this research due to the following methodological strengths:

The stepwise comparison logic enables experts to quantify precise importance gaps between consecutive criteria, resulting in a more sensitive weight distribution than traditional ranking techniques [39].

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The use of SFSs enables the representation of human hesitation through three independent parameters, thereby reducing information loss during the processing of linguistic evaluations [34,35].

The framework utilizes a mathematically concise algorithm that requires fewer pairwise comparisons, effectively reducing the cognitive load and time required from domain experts [40].

The procedural steps of the SF-SWARA method are outlined as follows:

Step 1: The process begins with expert-based linguistic evaluations of the relative importance of the criteria. These linguistic terms are converted into SFNs to represent membership, non-membership, and hesitation degrees simultaneously. Experts evaluate the relative importance criteria via linguistic terms provided in Table 1.

Table 1. Linguistic terms and associated fuzzy scales

Linguistic Terms	SFN (μ,v, π)
Extremely Low (EL)	(0.1, 0.9, 0.0)
Very Low (VL)	(0.2, 0.8, 0.1)
Low (L)	(0.3, 0.7, 0.2)
Fair (F)	(0.5, 0.5, 0.4)
High (H)	(0.7, 0.3, 0.2)
Very High (VH)	(0.8, 0.2, 0.1)
Extremely High (EH)	(0.9, 0.1, 0.0)

Step 2: Individual expert judgments are aggregated using the SWAM operator to obtain a collective group evaluation. Equal expert weights are used, since all experts are assumed to have the same decision-making importance in the analysis.

$$SWAM_w\left(\tilde{A}_{s_1},\tilde{A}_{s_2},\ldots,\tilde{A}_{s_n}\right) = \left\{\left[1 - \prod_{i=1}^{n}\left(1-\mu_{\tilde{A}_s}^2\right)^{w_i}\right]^{\frac{1}{2}}, \prod_{i=1}^{n} v_{\tilde{A}_s}^{w_i}, \left[\prod_{i=1}^{n}\left(1-\mu_{\tilde{A}_s}^2\right)^{w_i} - \prod_{i=1}^{n}\left(1-\mu_{\tilde{A}_s}^2-\pi_{\tilde{A}_s}^2\right)^{w_i}\right]^{\frac{1}{2}}\right\} \quad (3)$$

Step 3: The score function is applied to the aggregated SFNs to obtain crisp score values. These values are used only for ordering the criteria within the SF-SWARA procedure. A higher score indicates a higher perceived importance level.

$$S(\tilde{\alpha}) = \frac{1}{3}\left(2 + \mu_{\tilde{\alpha}}^2 - v_{\tilde{\alpha}}^2 - \pi_{\tilde{\alpha}}^2\right) \quad (4)$$

Step 4: The criteria are then ranked in descending order according to their score values.

Step 5: The relative importance of criteria are determined based on the ranking and the corresponding comparative coefficients are computed, where c_j expresses relative importance and k_j denotes the derived coefficient.

$$k_j = \begin{cases} 1, & j = 1 \\ c_j + 1, & j > 1 \end{cases} \quad (5)$$

Step 6: The criteria weights are iteratively recalculated using the comparative coefficients and subsequently normalized to obtain the final weight vector, where q_j

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represents the relative importance value of each criterion. The resulting weights sum to one and are used as input weights in the SF-CoCoSo ranking stage.

$$q_j = \begin{cases} 1, & j = 1 \\ \frac{q_{(j-1)}}{k_j}, & j > 1 \end{cases} \quad (6)$$

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \quad (7)$$

2.2. Ranking of Alternatives with SF-CoCoSo

Standard ranking techniques in MCDM often show high sensitivity to weight fluctuations, which can lead to inconsistent results and limited validity [41]. To resolve these issues, Yazdani et al. [42] (2019) proposed the CoCoSo method, which utilizes a variety of compromise indicators and aggregation strategies. This framework is highly effective at distinguishing between similar alternatives while maintaining superior precision and selectivity [43]. The current study applies the Spherical fuzzy extension of CoCoSo to prioritize the most suitable circular packaging options based on the criteria weights derived from SF-SWARA. The procedure begins by calculating weighted sum and weighted product sequences for each candidate [40]. This multi-layered logic ensures that the ranking remains stable and balanced by merging additive and multiplicative weighting paradigms, even when facing conflicting logistics objectives [44].

The SF-CoCoSo method is selected for this research due to the following methodological strengths:

The framework effectively mitigates the rank reversal problem, ensuring that the final order of alternatives remains stable against minor input changes [45].

By merging the mathematical advantages of weighted sum and weighted product models, the technique identifies a more resilient compromise solution than single-perspective approaches [40].

Utilizing SFSs allows for the independent representation of membership, non-membership and hesitancy, which significantly enhances the modeling of expert logic [34].

Step 1: Based on the linguistic scale provided in Table 1, each expert evaluates the performance of each alternative with respect to each sub-criterion.

$$\tilde{X} = [\tilde{x}_{ij}]_{m \times n} \quad (8)$$

Step 2: The expert-specific spherical fuzzy decision matrices are aggregated using the SWAM operator to obtain a single collective spherical fuzzy decision matrix. Equal expert weights are again used in this aggregation stage to maintain consistency with the criteria-weighting phase.

Step 3: Since the evaluation framework contains both benefit-type and cost-type criteria, the aggregated spherical fuzzy decision matrix is transformed according to criterion direction before the compromise calculations. This transformation ensures that all criteria follow a common preference logic in which higher values indicate better performance. For benefit-type criteria, the original SFN structure is retained. For cost-type criteria, the membership and non-membership degrees are exchanged so that lower original performance values are converted into more preferable transformed

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values. In this study, C21. Total cost of ownership, C61. Carbon footprint, and C63. Life-cycle impact are treated as cost-type criteria, whereas all remaining criteria are treated as benefit-type criteria.

Step 4: For each alternative A_i,

The weighted sum comparability $\tilde{s}_i$ is computed using Equation (12).

$$\lambda\tilde{\alpha} = S\left(\sqrt{1-(1-\mu_{\tilde{\alpha}}^2)^{\lambda}}, v_{\tilde{\alpha}}^{\lambda}, \sqrt{(1-\mu_{\tilde{\alpha}}^2)^{\lambda}-(1-\mu_{\tilde{\alpha}}^2-\pi_{\tilde{\alpha}}^2)^{\lambda}}\right) \tag{9}$$

$$\tilde{\alpha} \oplus \tilde{\beta} = S\left(\sqrt{\mu_{\tilde{\alpha}}^2+\mu_{\tilde{\beta}}^2-\mu_{\tilde{\alpha}}^2\mu_{\tilde{\beta}}^2},\ v_{\tilde{\alpha}}v_{\tilde{\beta}},\ \pi_{\tilde{\alpha}}^2\pi_{\tilde{\beta}}^2\right) \tag{10}$$

$$\tilde{s}_i = \sum_{j=1}^{n}(w_j\tilde{x}_{ij}) \tag{11}$$

The weighted product comparability $\tilde{p}_i$ is calculated using Equation (14).

$$\tilde{\alpha}^{\lambda} = \tilde{S}\left(\mu_{\tilde{\alpha}}^{\lambda}, \sqrt{1-(1-v_{\tilde{\alpha}}^2)^{\lambda}}, \sqrt{(1-v_{\tilde{\alpha}}^2)^{\lambda}-(1-v_{\tilde{\alpha}}^2-\pi_{\tilde{\alpha}}^2)^{\lambda}}\right) \tag{12}$$

$$\tilde{p}_i = \prod_{j=1}^{n}(\tilde{x}_{ij})^{w_j} \tag{13}$$

The values $\tilde{s}_i$ and $\tilde{p}_i$ are subsequently converted into crisp scores using the score function.

Step 5: The relative performances of alternatives are analyzed using three compromise aggregation measures that combine additive and multiplicative components.

$$k_{ia} = \frac{s_i + p_i}{\sum_{i=1}^{m}(s_i + p_i)} \tag{14}$$

$$k_{ib} = \frac{s_i}{\min_i s_i} + \frac{p_i}{\min_i p_i} \tag{15}$$

$$k_{ic} = \frac{\gamma\, s_i + (1-\gamma)p_i}{\gamma \max_i s_i + (1-\gamma)\max_i p_i} \tag{16}$$

Here, γ controls the balance between these components $(0 \le \gamma \le 1)$.

Step 6: The final SF-CoCoSo score of each alternative is obtained by combining the three compromise measures. Alternatives are ranked in descending order of their final scores, where a higher score represents a more preferable circular e-commerce shipping pack alternative.

$$k_i = (k_{ia}k_{ib}k_{ic})^{1/3} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic}) \tag{17}$$

3. Results

This study aims to evaluate and prioritize circular e-commerce shipping pack alternatives within a sustainability and circularity-oriented decision framework. The

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criteria structure was developed through a two-stage process. In the first stage, relevant criteria were extracted from previous studies on sustainable packaging, circular packaging models, e-commerce logistics, reverse logistics, customer acceptance, and life-cycle environmental assessment. In the second stage, the initial criteria pool was reviewed by the expert panel to ensure its suitability for e-commerce shipping pack selection. During this review, criteria that were too broad, repetitive, or weakly related to the decision problem were eliminated or merged, while e-commerce-specific criteria such as closure integrity, volumetric efficiency, return compliance, traceability capability, and right-sizing were retained. As a result, the final criteria hierarchy was organized under six main dimensions: protective and functional performance, economic and operational efficiency, circularity and end-of-life alignment, reverse logistics feasibility, customer and user experience, and environmental impact. The finalized criteria and their definitions are presented in Table 2.

Table 2. Definitions of criteria

Criteria	Definition	
Protective and functional performance		
C11.Mechanical strength	The degree of physical resistance of the package against crushing, tearing, and deformation during handling, storage, and transportation.	20,40
C12.Damage prevention performance	The ability of the packaging system to prevent product breakage, leakage, spoilage, or loss of functionality during shipment.	40
C13.Closure integrity and resealability	The capability of the package to remain securely sealed during initial delivery and to be reclosed effectively for potential return flows.	18
Economic and operational efficiency		
C21.Total cost of ownership	The overall cost impact of the packaging system, including material, packing, transportation, return processing, and end-of-life management costs.	19,20, 46
C22.Volumetric and loading efficiency	The extent to which the package improves logistics-level space utilization in vehicles, warehouses, and delivery operations while reducing dimensional-weight penalties.	19,20, 46
C23.Pack-out efficiency	The degree to which the packaging solution can be applied quickly, easily, and with low labor effort during order fulfillment.	20
C24.Automation compatibility	The level of compatibility of the packaging solution with automated or semi-automated packing, labeling, and sorting systems.	19,20, 46
Circularity and end-of-life alignment		
C31.Reusability and service life	The intrinsic ability of the packaging to withstand multiple use cycles without substantial loss of physical and functional performance.	18,20
C32.Recyclability or composability pathway compatibility	The extent to which the packaging is technically and practically compatible with available recycling or composting systems.	46
C33.Recycled or renewable material content	The proportion of secondary recycled inputs or bio-based renewable materials incorporated into the packaging system.	46

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C34.Closed-loop recovery compatibility	The system-level potential of the packaging to be collected, recovered, and reintroduced into the same or similar packaging applications through a controlled circular flow.	46
Reverse logistics feasibility		
C41.Collection and network coverage	The availability and accessibility of collection points, transport links, and supporting infrastructure for packaging recovery.	47–49
C42.Return processing responsiveness	The speed and effectiveness of sorting, inspection, cleaning, and preparation activities for returned packaging.	18,47
C43.Information and traceability capability	The suitability of the packaging system for tracking usage, return status, location, and life-cycle related data.	47
C44.Return compliance potential	The likelihood that customers will return, separate, or channel the packaging appropriately after use.	18,47
Customer and user experience		
C51.Ease of use	The ease with which customers can open, handle, store, and, when necessary, prepare the package for return.	47
C52.Right-sizing and specification fit	The extent to which the package is appropriately matched to the specific product/order size, fragility, and shipment requirements without over-packaging or under-protection.	47
C53.Customer satisfaction and market fit	The extent to which the packaging solution aligns with customer expectations, brand perception, and market requirements.	46,47
Environmental impact		
C61.Carbon footprint	The total greenhouse gas emissions associated with raw material sourcing, production, transportation, use, and end-of-life stages of the packaging system.	19
C62.Waste reduction and value recovery	The extent to which the packaging system reduces waste generation and enables retained material, economic, or environmental value after use.	19,20, 46
C63.Life-cycle impact	The overall effect of the packaging system on energy use, resource consumption, and environmental burdens throughout its life cycle.	19,47

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The selection of the proposed circular e-commerce shipping pack alternatives was grounded in current packaging practices, expert evaluations, with particular attention to circularity, operational feasibility, customer experience, and environmental performance in e-commerce logistics. In this context, the alternatives were defined to represent distinct packaging configurations. Rather than focusing solely on packaging materials, the proposed alternatives were conceptualized as integrated shipping pack systems, including the outer packaging, filler, sealing components, and return-related structure where applicable. This approach enables a more realistic assessment of circular packaging decisions in e-commerce environments, where protection, fulfillment efficiency, return handling, and end-of-life management must be considered simultaneously. The alternative shipping pack options evaluated in this study are described below.

A1. Standard single-use recyclable shipping pack: A packaging system consisting of a corrugated cardboard outer box, paper-based void filler, recyclable paper tape, and a one-way delivery structure. It is designed for post-use disposal through existing municipal recycling streams and does not require an additional take-back mechanism.

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A2. Reusable shipping pack without deposit: A durable packaging system made of long-life materials and resealable components, designed for repeated use across multiple delivery cycles. It is intended to be collected through reverse logistics after use, but it does not include a direct financial incentive for customer return.

A3. Compostable shipping pack: A bio-based packaging system composed of compostable outer packaging, filler, and sealing components. It is designed for end-of-life treatment through organic waste processing systems in contexts where suitable composting infrastructure is available.

A4. Deposit-return reusable shipping pack: A standardized and durable packaging system designed for repeated use over multiple shipping cycles. A refundable deposit is charged before delivery, and closed-loop reuse is enabled through customer return via designated collection or pickup channels.

A5. Minimal-pack / right-sized shipping pack: A lightweight and material-efficient packaging system designed to reduce package volume, filler use, and dimensional-weight penalties. It emphasizes source reduction while maintaining an acceptable level of product protection and delivery performance.

A panel of five experts with relevant academic and professional experience was formed to support the evaluation process. The expert group was intentionally structured to reflect the multidimensional nature of circular e-commerce packaging decisions. The panel included one expert specializing in packaging systems and material performance, one expert with experience in e-commerce fulfillment and logistics operations, one expert focusing on reverse logistics and circular supply chain management, one expert working on sustainability assessment and environmental evaluation, and one expert specializing in multi-criteria decision-making and fuzzy decision analysis. The experts had approximately 7 to 15 years of professional or academic experience in their respective fields. Their combined expertise was considered relevant to the study because the evaluation problem requires simultaneous consideration of packaging protection, operational efficiency, recovery infrastructure, customer-related issues, environmental performance, and uncertainty-based decision modeling. Individual consultations were conducted to ensure a common understanding of the assessment procedure and the spherical fuzzy linguistic scale used in the study. The experts contributed to three main stages of the research: (i) identifying and refining the evaluation criteria, (ii) determining the relative importance of the criteria, and (iii) assessing the proposed circular e-commerce shipping pack alternatives. All evaluation forms were completed independently by each expert, which helped maintain the objectivity and consistency of the judgments.

3.1 Calculation of criteria weights with SF-SWARA

To ensure a consistent and reliable evaluation process, expert judgments were systematically incorporated into the analysis after the criteria hierarchy had been finalized. After constructing the criteria hierarchy, all five experts participating in the study were treated equally during the evaluation stage. The experts independently evaluated the main criteria using the spherical fuzzy linguistic variables presented in Table 1. Drawing on their own expertise and practical understanding, each expert provided separate judgments, and these individual assessments were subsequently

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aggregated to generate the final decision matrix for the analysis. The main criteria evaluations provided by the experts are presented in Table 3.

Table 3. Expert evaluations for main criteria

Main criterion	E1	E2	E3	E4	E5
C1. Protective and functional performance	VH	EH	VH	H	EH
C2. Economic and operational efficiency	EH	EH	F	F	VH
C3. Circularity and end-of-life alignment	H	H	H	EH	H
C4. Reverse logistics feasibility	EH	H	H	VH	F
C5. Customer and user experience	F	VH	EH	F	H
C6. Environmental impact	H	H	VH	EH	VH

The linguistic evaluations were converted into SFNs using the scale in Table 1. The individual expert judgments were then aggregated with the SWAM operator under equal expert weights (see Table A1 in Appendix). The aggregated SFNs were converted into crisp score values through the score function (see Table A1 in Appendix), and the main criteria were ordered from the most important to the least important according to these scores. The remaining SF-SWARA steps were then applied to derive the normalized weights of the main criteria, as shown in Figure 2.

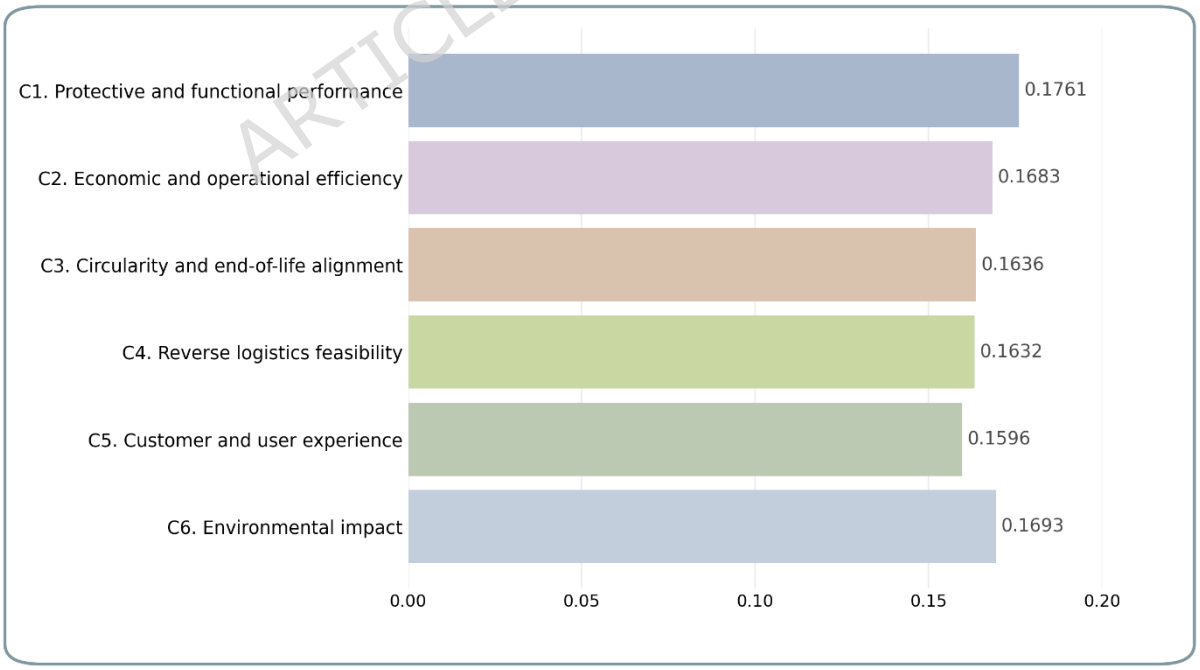


Figure 2. Main criteria weights

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The weighting results show that Protective and functional performance (C1) emerged as the most important main criterion in the assessment framework. On the other hand, Customer and user experience (C5) had the lowest weight, indicating a comparatively lower contribution to the overall evaluation than the remaining main criteria.

The same panel of experts was also consulted to develop the evaluation matrices for the sub-criteria used to assess circular e-commerce shipping pack alternatives. The experts independently evaluated the sub-criteria using the same spherical fuzzy linguistic framework adopted for the main criteria. Based on these judgments, the local weights of the sub-criteria were obtained by reapplying the SF-SWARA procedure. To derive the global weights, each local sub-criterion weight was multiplied by the weight of its corresponding main criterion. Table 4 reports the expert evaluations together with the local and global weights of the sub-criteria.

Table 4. Expert evaluations and local-global weights of the sub-criteria

Sub criterion	E1	E2	E3	E4	E5	Local Weight	Final Weight
C11. Mechanical strength	H	EH	H	H	VH	0.3319	0.0584
C12. Damage prevention performance	VH	EH	EH	VH	EH	0.3611	0.0636
C13. Closure integrity and resealability	H	H	H	H	H	0.3071	0.0541
C21. Total cost of ownership	EH	EH	F	F	EH	0.2736	0.046
C22. Volumetric and loading efficiency	VH	VH	F	H	VH	0.2544	0.0428
C23. Pack-out efficiency	H	VH	F	F	H	0.2364	0.0398
C24. Automation compatibility	VH	VH	L	L	H	0.2356	0.0396
C31. Reusability and service life	H	F	H	EH	H	0.2543	0.0416
C32. Recyclability or compostability pathway compatibility	H	H	VH	EH	VH	0.2604	0.0426
C33. Recycled or renewable material content	F	L	H	VH	F	0.2258	0.0369
C34. Closed-loop recovery compatibility	VH	F	H	EH	H	0.2595	0.0424
C41. Collection and network coverage	EH	H	H	VH	VH	0.2629	0.0429
C42. Return processing responsiveness	VH	H	F	H	H	0.2383	0.0389
C43. Information and traceability capability	VH	VH	H	H	F	0.2441	0.0398
C44. Return compliance potential	H	H	VH	VH	VH	0.2548	0.0416
C51. Ease of use	H	H	EH	F	H	0.3297	0.0526
C52. Right-sizing and specification fit	H	VH	EH	H	VH	0.3486	0.0556
C53. Customer satisfaction and market fit	F	H	EH	F	H	0.3217	0.0513
C61. Carbon footprint	H	F	VH	EH	VH	0.328	0.0555
C62. Waste reduction and value recovery	H	H	VH	EH	VH	0.3341	0.0566
C63. Life-cycle impact	H	F	VH	EH	EH	0.3379	0.0572

The sub-criteria results reveal a clear emphasis on shipment protection, environmental performance, and packaging fit within the proposed evaluation framework. Among all sub-criteria, Damage prevention performance (C12) received the highest final weight, indicating that experts considered the ability of a shipping pack to prevent product damage during transportation as the most critical factor. This was followed by Mechanical strength (C11) and Life-cycle impact (C63), highlighting the

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importance of both physical protection and broader environmental consequences in circular e-commerce packaging decisions. Waste reduction and value recovery (C62), Right-sizing and specification fit (C52), and Carbon footprint (C61) also obtained relatively high final weights, suggesting that experts gave considerable priority to packaging solutions that minimize unnecessary material use, improve shipment efficiency, and reduce environmental burdens.

3.2 Ranking the alternative strategies with SF-CoCoSo

The circular e-commerce shipping pack alternatives were ranked using the SF-CoCoSo method. To ensure consistency and comparability throughout the evaluation process, each expert assessed all alternatives under each sub-criterion by using the same spherical fuzzy linguistic variables presented in Table 1. The individual evaluation matrices obtained from the experts are provided in Table A2 (see Appendix). Subsequently, the linguistic evaluations were converted into SFNs to construct the decision matrices of the experts. All experts were treated equally during this stage, and the individual matrices were aggregated using the SWAM operator to obtain the collective decision matrix, as given in Table A3 (see Appendix). Since all alternatives were evaluated by experts under a common linguistic scale for the same set of criteria, no additional normalization was required at this stage of the analysis.

Subsequently, the aggregated alternative evaluation matrix was processed to enable a consistent comparison across all criteria. Based on this collective matrix, the appraisal values of the alternatives were derived under the SF-CoCoSo framework by incorporating the previously obtained criterion weights from the SF-SWARA method. In this stage, C21. Total cost of ownership, C61. Carbon footprint, and C63. Life-cycle impact were treated as cost-type criteria, whereas all remaining criteria were considered benefit-type criteria. The overall priority order of the circular e-commerce shipping pack alternatives was then established according to their integrated performance scores, and the final ranking results are presented in Table 5. For $\lambda = 0.5$, the strategies were ranked as follows: A4 ≻ A1 ≻ A5 ≻ A2 ≻ A3.

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Table 5. The ranking of the strategies ($\lambda = 0.5$)

Alternative	k_{ia}	k_{ib}	k_{ic}	k_i	Rank
A1. Standard single-use recyclable shipping pack	0.2	2.20	0.972	1.854	2
A2. Reusable shipping pack without deposit	0.19	2.10	0.960	1.827	4
A3. Compostable shipping pack	0.191	2.000	0.921	1.774	5
A4. Deposit-return reusable shipping pack	0.208	2.220	1.000	1.915	1
A5. Minimal-pack / right-sized shipping pack	0.200	2.115	0.962	1.833	3

The results indicate that A4. The deposit-return reusable shipping pack achieved the highest overall performance score and ranked first among the evaluated

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alternatives. This finding suggests that combining reusability with a deposit-based return mechanism provides a stronger circular packaging solution by improving return compliance and supporting closed-loop use. A1. The standard single-use recyclable shipping pack ranked second, showing that operationally simple, infrastructure-compatible solutions still perform strongly in e-commerce settings. A5. Minimal-pack/right-sized shipping pack came in third place, reflecting the value of source reduction and volumetric efficiency. In contrast, A2. Reusable shipping pack without deposit ranked fourth, implying that reusability alone may not be sufficient without an effective return incentive. A3. Compostable shipping pack received the lowest rank, indicating that its performance may remain limited when composting infrastructure and recovery conditions are less favorable.

3.3 Sensitivity Analysis

A sensitivity analysis was conducted to examine the effect of changes in the λ parameter on the ranking of the circular e-commerce shipping pack alternatives. For this purpose, the λ value was systematically varied from 0 to 1 at equal intervals, and the resulting alternative scores are reported in Figure 3.

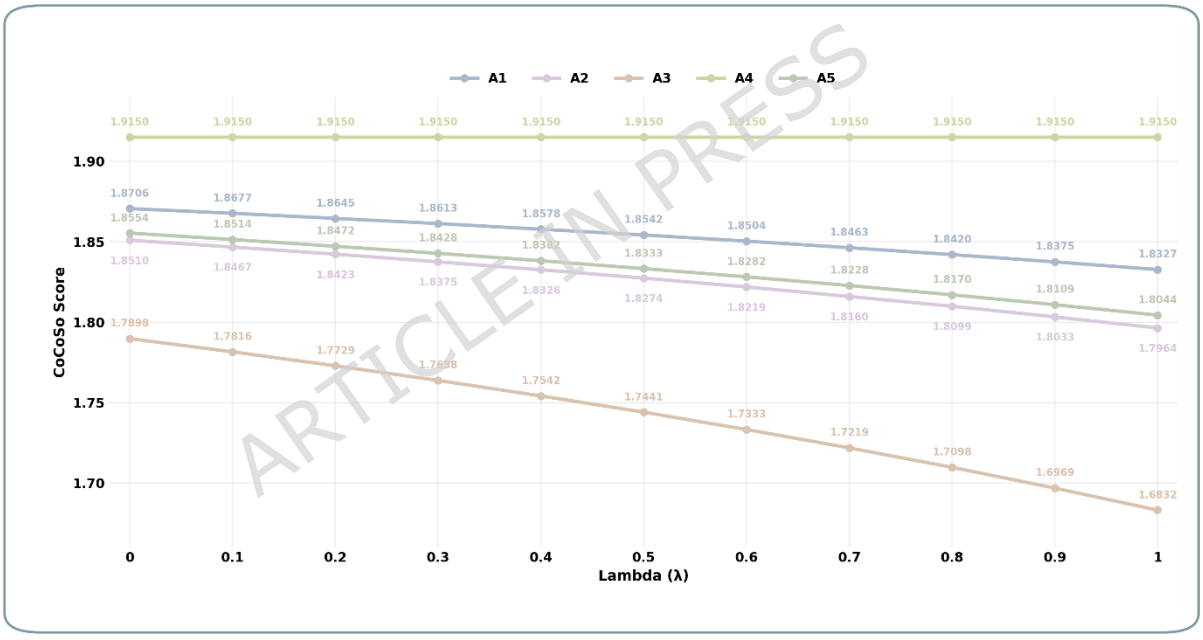


Figure 3. Sensitivity analysis of SF-CoCoSo scores with respect to λ values

The sensitivity analysis results show that varying the λ parameter did not alter the ranking order of the evaluated alternatives, indicating a high degree of stability in the SF-CoCoSo results. Across all tested λ values, A4. Deposit-return reusable shipping pack consistently maintained the first position, while A3. Compostable shipping pack remained the lowest-ranked alternative. Similarly, the relative positions of A1, A5, and A2 did not change throughout the analysis. Although the alternative scores exhibited slight numerical variations as λ increased, these changes were not strong enough to affect the overall priority order. This finding confirms that the proposed ranking

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structure is robust to changes in the λ parameter and that the superiority of the leading alternative is not dependent on a specific parameter setting.

4. Discussion

The results indicate that circular e-commerce packaging performance depends not only on material selection but also on the effectiveness of the overall system in which the packaging operates. The high weight assigned to protective and functional performance, particularly to damage prevention, shows that circularity cannot be considered separately from logistics reliability.

The fact that protective and functional performance emerged as the most influential main criterion, and that damage prevention performance received the highest global weight, confirms that packaging in e-commerce remains fundamentally a logistics safeguard rather than a purely environmental object. This weighting pattern is theoretically important because any circular gain can be rapidly neutralized when insufficient protection leads to product damage, replacement shipments, additional handling, and avoidable waste. In this respect, the present study supports the view that circularity should be assessed alongside service reliability rather than in isolation.

The first-place position of the deposit-return reusable shipping pack (A4) demonstrates that reuse becomes genuinely competitive when it is embedded in a structured return architecture. This outcome is consistent with earlier studies emphasizing the role of reverse logistics, repeated circulation, and recovery design in online retail systems [7,8]. It also aligns with research showing that reusable packaging generates superior environmental and operational outcomes only when return participation, network coordination, and system intensity are sufficiently strong [13,14]. Accordingly, the advantage of A4 appears to arise not only from the durability of the package itself, but also from the presence of an incentive-compatible mechanism that improves return compliance and supports closed-loop circulation. In this sense, the findings suggest that reusability should be understood as a service-system capability rather than as a stand-alone material attribute [10,11,15]. A2's lower performance indicates that reuse alone may remain fragile when the behavioral and logistical conditions required for package return are not adequately reinforced. Although customer and user experience received the lowest weight among the main criteria, this should not be interpreted as evidence of irrelevance. Rather, it suggests that experts viewed convenience-related dimensions as indirect enablers whose influence becomes visible through return compliance, market fit, and participation rates.

The relatively strong standing of the standard single-use recyclable shipping pack (A1) is likewise instructive. Although this option does not provide the repeated-use potential of reusable systems, it benefits from operational simplicity, compatibility with existing collection and recycling arrangements, and lower implementation friction. This pattern is in line with studies arguing that reusable formats are not universally preferable and that sustainability outcomes depend heavily on infrastructure maturity, use intensity, and recovery conditions [9,12–14]. From a managerial standpoint, this implies that firms operating in markets where reverse logistics remains fragmented may still achieve meaningful improvements through recyclable, operationally mature solutions.

The performance of the minimal-pack/right-sized alternative (A5) further highlights the strategic value of source reduction. Its ranking indicates that minimizing space,

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filler intensity, and dimensional inefficiency can generate substantial system-level benefits, particularly in e-commerce environments where transport utilization and volumetric charging strongly affect both cost and environmental impact. It also suggests that circularity should not be reduced to end-of-life recovery alone; upstream design decisions that prevent unnecessary material use may create value before recycling, composting, or reuse even becomes relevant.

By contrast, the last-place position of the compostable shipping pack (A3) illustrates the limits of material innovation when supporting infrastructure is weak or inconsistent. Compostable solutions may appear environmentally attractive at the conceptual level, yet their actual performance depends heavily on collection practices, processing capacity, contamination control, and user compliance. This interpretation accords with previous research showing that the sustainability of e-commerce packaging is context-dependent and mediated by institutional support, local infrastructure, and real end-of-life pathways [6,12–15]. In the broader policy context, the findings imply that enabling systems—such as standardized collection channels, digital traceability, and incentive mechanisms—may shape circular outcomes more profoundly than isolated shifts in material selection.

From a methodological perspective, the stability of the rankings across different λ values further strengthens confidence in the proposed framework. The persistence of the order indicates that the leading alternative did not emerge from a fragile parameter setting, but from a structurally consistent decision pattern.

Moreover, the integration of SF-SWARA and SF-CoCoSo proved particularly suitable for a problem characterized by interdependent criteria, expert hesitation, and conflicting sustainability objectives. By allowing membership, non-membership, and hesitancy to be expressed independently, the spherical fuzzy environment captured decision ambiguity more effectively than conventional crisp or more restrictive fuzzy representations.

The evaluation is based on a relatively small expert panel and reflects a generalized e-commerce setting rather than a sector-specific or region-specific application. In practice, recovery rates, contamination risks, return economics, product fragility, and infrastructure maturity may vary substantially across markets, potentially altering the relative attractiveness of the alternatives. Future studies could therefore combine the proposed framework with empirical life-cycle assessment, cost simulation, consumer experiments, and scenario-based analyses of return behavior. Cross-country comparisons, product-category-specific applications, and studies using real operational data would be especially valuable for testing whether the advantage of deposit-return systems persists under different logistical and institutional conditions.

5. Conclusions

This study developed an integrated spherical fuzzy MCDM framework to evaluate circular e-commerce shipping pack alternatives by combining SF-SWARA for criteria weighting and SF-CoCoSo for alternative ranking. The analysis showed that protective and functional performance constitutes the dominant decision domain, with damage prevention performance emerging as the most influential sub-criterion. These findings lead to an important substantive conclusion: in e-commerce, the circular value of a shipping pack is shaped less by the declared sustainability profile of its materials than

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by the coherence of the system in which it operates. Recovery incentives, reverse logistics capability, infrastructure compatibility, protective performance, and user participation jointly determine whether a packaging concept can deliver superior outcomes in practice. The study therefore supports a shift in perspective from material-centered evaluation toward system-centered circular design.

From a managerial standpoint, the results indicate that firms seeking to improve packaging sustainability should prioritize alternatives that combine strong product protection with credible recovery pathways and operational feasibility. Deposit-return structures appear particularly promising where collection networks, traceability systems, and return compliance can be effectively organized. At the same time, recyclable and right-sized configurations may serve as realistic transition strategies in markets where closed-loop reuse is not yet fully mature. Overall, the study shows that the future of circular e-commerce packaging lies not in greener materials alone, but in recoverable systems that maintain functionality, value, and participation in continuous circulation.

This framework also contributes to the literature by consolidating fragmented discussions on packaging design, reverse logistics, circular economy, and consumer participation into a unified decision architecture under uncertainty. In this sense, the study argues that the most effective circular shipping pack is not merely an alternative container, but a logistics interface designed to preserve product integrity while continuously reactivating material value across multiple stages of the e-commerce system.

Despite its contributions, this study has several limitations that should be considered when interpreting the findings. First, the evaluation was conducted with a relatively small expert panel, and future studies may involve a larger and more diverse group of experts from e-commerce firms, packaging manufacturers, logistics providers, and recycling or recovery organizations. Second, the analysis was based on expert judgments rather than real company-level operational data. Therefore, future research could integrate actual data on order volumes, product categories, packaging costs, damage rates, return rates, customer participation, and reverse logistics performance. Third, the results may vary across regions because recycling systems, composting facilities, collection networks, logistics density, and consumer behavior differ substantially between markets. In particular, the performance of reusable and deposit-return packaging systems is highly dependent on return compliance, reuse cycles, cleaning and inspection requirements, and recovery infrastructure. Future studies could therefore apply the proposed framework to specific companies, regions, or product categories and combine it with life-cycle assessment, cost simulation, customer experiments, and scenario-based return-rate analysis. Such extensions would help test the robustness of the proposed ranking and improve the practical applicability of circular e-commerce shipping pack selection under different market conditions.

Use of Experimental Animals, And Human Participants: Expert evaluations were conducted within the scope of MCDM framework; no personal or sensitive data were collected, ethical committee approval was not required, and informed consent was obtained from all participating experts. All methods were performed in accordance with the relevant guidelines and regulations, and no live animals were used in this study.

Author Contributions: Conceptualization, E.A., M.C., and N.A.; methodology, M.C.; formal analysis, E.A., M.C., and N.A.; data curation, T.K.K and B.Y.K.; writing—original draft

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preparation, B.Y.K and M.C; writing—review and editing, T.K.K., E.A. and N.A.; supervision, B.Y and N.A. All authors have read and agreed to the published version of the manuscript.

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