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Spherical fuzzy decision support approach to evaluate the sustainable strategies in agri-food supply chains: A case study in tea supply chain

Betul Yildirim [a], Ertugrul Ayyildiz [b,c], Nezir Aydin [b,d,*]

[a] Department of Industrial Engineering, Hasan Kalyoncu University, Gaziantep, Türkiye
[b] College of Science and Engineering, Hamad bin Khalifa University, Doha, Qatar
[c] Department of Industrial Engineering, Karadeniz Technical University, Trabzon, Türkiye
[d] Department of Industrial Engineering, Yildiz Technical University, Istanbul, Türkiye

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ABSTRACT

This study proposes a novel sustainability-focused model for evaluating agri-food supply chains, illustrated by a Turkish tea supply chain case ensuring environmental, economic, and social benefits. The research aims to assess and prioritize strategies for enhancing sustainability by identifying key criteria within the sustainability framework. We identify and weigh comprehensive environmental, social, economic, and technical criteria, then rank five strategies aimed at long-term resilience and efficiency. Findings reveal low R&D investment as a major barrier while adopting digital technologies emerges as the most effective solution. These results highlight the novelty of sustainability in our framework, guiding stakeholders toward more balanced decisions.

1. Introduction

Supply chain has become a frequently used concept for planners and academics since the 1980s [1]. Supply Chain Management (SCM) literature deals with the supply chain formed by transforming raw materials into products and delivering them to consumers, combining various disciplines and enabling the formation of several research streams. The SCM concept has become more complex. Its definition considers multiple participants, layers, flows, purposes, and activities [2]. To meet the global demand for tea consumption and increase their market share, competitive and sustainable agriculture is essential for companies [3]. Since agricultural products are a fundamental component of human life, they play a critical role in ensuring that individuals take all vital nutrients. Therefore, governments and facilities spend substantial economic resources and adjust their policies to advance a stable agricultural food supply chain [4].

In this paper, we considered sustainability for the tea supply chain and proposed a novel sustainability assessment model. This study aims to determine the most appropriate sustainable supply chain strategy by determining detailed criteria. In the first step, we calculated the sub-criteria weights, which we classified under environmental, financial, social, and technical main groups, by a novel approach, the Spherical Fuzzy PIvot Pairwise Relative Criteria Importance Assessment (SF-PIPRECIA) method. By introducing SF-PIPRECIA to the literature, the study aims to enhance a robust framework and reliability for the criteria weighting process under uncertainty. Then, we defined five different strategies within the sustainability framework for the agri-food supply chain (ASC). Using the obtained criteria weights, we also ranked the alternative strategy by the Spherical Fuzzy Combinative Distance-Based Assessment (SF-CODAS) method. Thus, for the first time in the literature, the SF-PIPRECIA method was integrated into the SF-CODAS method. Integrating SF-PIPRECIA and SF-CODAS enables the uncertainty and complexity in decision-making processes to be evaluated comprehensively. This has led to the identification of the most sustainable management strategy for the ASC.

1.1. Motivations of the study

In recent years, the concept of sustainability has become a significant topic in global forums, emphasizing the necessity of sustainability for organizations' business activities [5]. Sustainability can be thought of as the degree of impact of organizations' current decisions on the environment and the future of business [6]. It provides companies with cost reduction, increased efficiency, and competitive advantage. Companies and their internal and external stakeholders should focus on sustainability strategically and tactically [7]. Sustainable Supply Chain

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* Corresponding author at: College of Science and Engineering, Hamad bin Khalifa University, Doha, Qatar.
E-mail address: naydin@hbku.edu.qa (N. Aydin).

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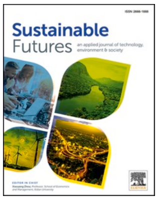

Management (SSCM) has emerged from the inclusion of a sustainability perspective in management [2]. Based on these definitions, sustainability strategies should consider investment costs, future uncertainty, and risks and make supply chains more sustainable [8]. In addition to environmental and social criteria for SSCM, economic criteria must be considered to maintain competitiveness [9].

One of the types of SCM that has attracted attention from researchers in recent years is the ASC. ASC comprises procurement, production, post-harvest, storage, processing, and distribution stages [10]. Although ASC has similarities with traditional supply chains, it has a more complex structure [11]. Because most of the food types are perishable products [12]. In addition, demand and price variability make ASC more challenging and complex to manage than other supply chains [13]. Therefore, companies must adopt the most appropriate management strategies to overcome these difficulties by considering many criteria.

The contributions of this study are summarized:

- The most applicable management strategies for the tea supply chain were determined using a novel Multi-Criteria Decision Making (MCDM) approach.
- An extensive number of criteria within the sustainability framework were determined, including environmental, financial, social, and technical as the main criteria.
- For the first time in literature, the SF-PIPRECIA method was used to weigh the criteria. SF-CODAS was applied using determined criteria weights to obtain the scores of alternative strategies. So, unlike the literature, PIPRECIA and CODAS methods within the spherical fuzzy environment were integrated.

Section 2 offers a brief literature review of relevant studies with SSCM and ASC. Section 3 shows the proposed methodology. Section 4 presents the real case study, the discussion is given in Section 5, and Section 6 presents concluding remarks and directions for future works.

2. Literature review

In recent years, with the concept of sustainability coming to the fore, there have been many studies on this field, especially in supply chain management, but the studies on agri-food are limited. Agrifood Supply Chain Management (ASCM) is an important issue affecting countries' economies, the country's future, and authorized companies. The tea industry, one of the foods that fall within the scope of this important issue and has a high consumption rate, has not been addressed before to select a sustainable management strategy. Moreover, studies on the tea industry's supply chain are very limited. In this section, we researched sustainable supply chain management, ASC, and spherical fuzzy methodology literature in detail according to the purpose of the studies, research area, and method and presented summary tables.

SSCM has a very extensive literature. Many studies in the literature conducted detailed literature reviews of SSCM [2,5,14–20]. Research on SCM primarily focuses on environmental, economic, and social impacts, known as the Triple Bottom Line-TBL [21]. Although the TBL framework is often discussed in relation to economic benefits, some studies have emphasized its social and economic benefits [14,22–25]. The related studies found in the literature that stand out with some unique aspects are summarized in Table 1.

The ASC literature consists of several studies, reviews [40–43], and bibliometric analyses [12,44], which are valuable sources in ASC. In addition, some other studies on this subject in literature are summarized in Table 2.

The ASC is inherently complex, encompassing a wide range of activities from producing and processing to distributing and consuming [55,56]. Grain-based commodities such as wheat, rice and corn are particularly sensitive to disruptions due to resource constraints, environmental risks and volatile demand [57]. To manage these uncertainties, researchers and practitioners have increasingly turned to fuzzy logic and fuzzy set theory, which provide a robust framework for handling inaccurate data and linguistic assessments [58–60]. An important application of fuzzy logic in agri-food supply chains is in the selection of suppliers, an MCDM challenge that involves the reconciliation of conflicting attributes such as price, quality and sustainability performance [61–63]. Fuzzy models allow decision-makers to incorporate subjective judgments, such as environmental practices and social responsibility, into quantitative rankings [64]. The use of fuzzy analytical network process (FANP) or fuzzy VIKOR methods has helped organizations to identify the most suitable suppliers while maintaining

Table 1
Summary of sustainable supply chain management studies.

Refs.	Objective	Research area	Method
[26]	Exploring the most reasonable functions of a Sustainable Supply Chain for possible blockchain implementations	Blockchain	Fuzzy SWARA-COPRAS-EDAS and COPELAND
[27]	Calculating sustainability in the supply chain	Renewable energy	Fuzzy Inference Systems
[28]	Supplier selection based on sustainable factors	Producer of industrial valves, fittings, and pipes	Fuzzy TOPSIS
[29]	Supplier selection based on sustainable factors	Forklift truck manufacturer	Fuzzy MULTIMOORA, Best Worst Method (BWM)
[30]	Evaluate and compare the company's performances	Grocery retailer	Fuzzy entropy, Multiple Attribute Utility Theory
[31]	Determine the best-performing organizations	Green supply chain	Fuzzy AHP, fuzzy VIKOR
[8]	Identifying selected risks and their potential causes and impacts and testing potential correlations between identified risks.	Risk management	Failure mode and effect analysis
[24]	Evaluate the suitability of different locations for photovoltaic energy production.	Renewable energy	AHP
[32]	Designing and planning of closed-loop supply chains	Lead battery producer and distributor	Multi-objective mathematical programming
[33]	Investigate the impact of lean, resilient, and green supply chain management practices.	Automotive supply chain	A deductive research approach
[34]	Training assessment for green supply chain management (GSCM)	Green supply chain-chemical industry	AHP, Supply Chain Operations Reference Model
[35]	Evaluating and ranking the GSCM performance of alternative companies	Machine manufacturing	Fuzzy DEMATEL, fuzzy ANP, fuzzy TOPSIS
[36]	Sustainable strategy selection	Manufacturing industry	AHP, SOWIA, TOPSIS
[37]	Addressing social sustainability for supplier selection	Footwear industry	BWM
[38]	Sustainable supplier selection	Textile manufacturing	Fuzzy preference programming, fuzzy TOPSIS
[39]	Sustainable supplier selection	Lamp supply chain	Fuzzy DEMATEL, fuzzy ANP, fuzzy TOPSIS, weighted goal programming

SWARA: Step-wise Weight Assessment Ratio Analysis; COPRAS: Complex Proportional Assessment; EDAS: Evaluation Based on Distance from Average Solution; COPELAND: An extended version of the Borda method; TOPSIS: Technique for Order Preference by Similarity to Ideal Solution; MULTIMOORA: Multi-Objective Optimization based on a Ratio Analysis plus the full MULTIplicative form; AHP: Analytic Hierarchy Process; VIKOR: VlseKriterijuska Optimizacija I Komoromisno Resenje; DEMATEL: Decision-Making Trial and Evaluation Laboratory; ANP: Analytic Network Process; SOWIA: subjective and objective weight integrated approach; BWM: Best Worst Method.

Table 2
Summary of ASC studies.

Refs.	Objective	Research area	Method
[45]	Proposing an innovative and sustainable ASC model	Olive oil	Food supply chain model
[46]	Exploring the link between ASCs and circular economy levels	Sugar cane	Cascade chain theory
[47]	Green supplier selection	Food goods	Fuzzy MABAC, MARCOS, CRADIS
[4]	ASC network design	Coconut industry	Mixed-integer linear programming model, Non-Dominated Sorting Genetic Algorithm-II, MCDM
[48]	Maximizing total profit and customer satisfaction and reducing water consumption	Saffron industry	Multi-objective optimization model, convex robust optimization, MCDM
[49]	Selecting suppliers, transformer sites, and critical distribution hubs	Raw materials	Multi-objective mixed-integer programming, COPRAS, BWM
[50]	Develop and analyze a mathematical model with a perishable product in agricultural food	Organic and conventional agricultural products	multi-objective linear mathematical model
[51]	Researching coordination strategies	Fresh agricultural products	Dynamic game models
[52]	Coordinate fresh agricultural product supply chain with strategic consumer behavior.	Fresh agricultural products	Two-period newsvendor model
Ahumada and Villalobos, 2011	Helping growers maximize their income by making production and distribution decisions during the harvest season	Perishable products	Mixed integer programming
[53]	Vehicle scheduling and routing	Cross-docking	Mixed-integer linear programming
[54]	Minimizing effects of the disruption	Perishable products	Multi-objective mixed-integer programming, augmented ε-constraint method
This paper	Sustainable strategy selection	Tea supply chain	SF-PIPRECIA, SF-CODAS

MABAC: Multi-Attributive Border Approximation Area Comparison; MARCOS: Measurement of alternatives and ranking according to COmpromise solution; CRADIS: Compromise Ranking of Alternatives from Distance to the Ideal Solution.

balanced trade-offs between different criteria [61]. Beyond supplier selection, fuzzy logic has also proven valuable in risk assessment and resilience evaluation [57,65]. For grain supply chains, disruptions can arise from extreme weather events, logistical bottlenecks or market volatility, which often have high levels of uncertainty. Fuzzy approaches address these challenges by representing the likelihood and impact of risks through membership functions, thereby capturing expert opinions and incomplete data in a structured way [66]. Recent studies have adopted fuzzy DEMATEL-ISM and fuzzy cross-impact matrix multiplication applied classification (MICMAC) to model interdependencies among risk factors, thus providing more realistic and proactive strategies for mitigating disruptions [57,67].

Traceability and transparency also rank high among current concerns in grain supply chains. Implementation of blockchain, coupled with fuzzy logic, offers a solution by recording each transaction or movement of grain on an immutable ledger and then applying fuzzy methods to evaluate product quality or safety indicators [68,69]. This synergy enables real-time monitoring of storage conditions, predictive maintenance of transport fleets, and improved trust among all stakeholders. Likewise, big data analytics and artificial intelligence (AI) can be integrated with fuzzy frameworks to optimize resource allocation, forecast demand further, and streamline operations across multiple levels of the agri-food network [70,71].

In summary, fuzzy logic has emerged as an influential methodology for addressing the many uncertainties in grain and other agri-food supply chains. Applications range from supplier selection to risk management and traceability solutions, underscoring the adaptability and relevance of fuzzy frameworks. Moving forward, there is scope for further integration of emerging technologies—such as AI, blockchain, and the Internet of Things (IoT)—into fuzzy decision models, which can enhance sustainability, efficiency, and resilience in agri-food supply chains [72,73].

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Fuzzy logic has emerged as an influential methodology for addressing the many uncertainties in grain and other agri-food supply chains. Applications range from supplier selection to risk management and traceability solutions, highlighting the adaptability and relevance of fuzzy frameworks. From now on, there is scope to further integrate emerging technologies - such as AI, blockchain and the Internet of Things (IoT) - into fuzzy decision models, which can improve the sustainability, efficiency and resilience of agri-food supply chains [72,73].

According to Tables 1 and 2, the management strategy selection in sustainable ASC has yet to be addressed in the literature. Table 2 shows the limited number of ASC studies generally on mathematical modeling. The inadequacy of the multi-criteria decision-making methods used effectively in important decision-making problems such as location and strategy selection is striking in this field. Additionally, Table 2 shows that studies on ASCs generally focus on supply chain network design or supplier selection. In addition, despite focusing on different types of agri-food, a sustainable supply chain has not been addressed for tea, an important source of income for a specific part of the population in some countries such as Turkiye and is consumed a lot globally. This study selects the most suitable strategy for the tea supply chain with a novel MCDM approach considering sustainability, a popular and essential framework for SCM. Table 3 summarizes some important studies in the literature using spherical fuzzy sets-based methods. The most notable of these studies is the research that aims to determine the best sustainable green strategy in a similar way presented by [74]. The study was conducted for logistics companies, and the hybrid T-spherical fuzzy (T-SF) methodology was used. Five green sustainable energy strategies were evaluated under criteria such as cost and technical barriers with literature research.

3. Methodology

The growing complexity of ASCs and the increasing demand for sustainable practices pose significant challenges for producers, suppliers, and policymakers. In particular, environmental degradation, inefficient resource use, and limited technology adoption are challenges facing the tea supply chain in Turkiye. A structured approach to assessing and prioritizing sustainability strategies is required to address these challenges. As traditional methods may not fully capture the multifaceted nature of sustainability in agri-food systems, a reliable framework to evaluate different sustainability factors in supply chains has become critical. To address this problem, this study aims to develop a comprehensive decision-making methodology that evaluates and

Table 3
Summary of spherical fuzzy sets studies.

Refs.	Objective	Research area	Method
[75]	Solving a multiple criteria selection problem	3D printers	SF-TOPSIS
[76]	Evaluate the food circulation center	Food circulation center	Spherical fuzzy t’-norm, spherical fuzzy t’-conform
[75]	Selection of industrial robots	Robot industry	SF-WASPAS
[77]	Manufacturing system selection	Tractor components	SF-AHP, SF-TOPSIS
[78]	Offer a sustainable solution for the public bus transport system	Sustainable urban transport	SF-AHP
[74]	Selection of sustainable green strategy	Logistic	Hybrid T-spherical fuzzy
[79]	Renewable energy selection	Renewable energy	SF-DEMATEL, SF-ANP, SF-VIKOR
[80]	Evaluate risk mitigation strategies	Offshore wind farms	SF-SWARA, SF-VIKOR
[81]	Selection of enterprise resource planning system	ERP system	Spherical fuzzy Hamy mean, complex spherical fuzzy Dual Hamy mean
[82]	Emergency location selection	Emergency temporary hospital during the COVID-19 pandemic location	Spherical weighted arithmetic mean, spherical aggregation operator
[83]	Ranking of the states for business climate	Indian states	SF-AHP

WASPAS: Weighted Aggregated Sum Product Assessment; SWARA: Improved Fuzzy Stepwise Weight Assessment Ratio Analysis

ranks alternative strategies for improving sustainability in the tea supply chain. The proposed approach provides an innovative way to model uncertainty and hesitancy in expert judgments by employing a novel integration of the spherical fuzzy environment with decision-making techniques. The combination of criteria weighting and strategy evaluation methods provides a more nuanced analysis and contributes to the literature by extending the application of fuzzy decision-making in sustainability contexts. This study makes several novel contributions to literature. First, it extends the PIPRECIA method by incorporating spherical fuzzy numbers, introducing the SF-PIPRECIA model. This extension allows for better handling of uncertainty and hesitancy in expert judgments. In addition, the study pioneers the combination of PIPRECIA with the CODAS method, offering a new hybrid approach to multi-criteria decision-making. Beyond methodological advances, this research proposes the first comprehensive sustainability assessment model tailored to the ASC. In doing so, it fills a critical gap in the literature and provides a robust framework for improving sustainability practices in the sector.

In this study, we proposed a two-level criteria hierarchy to determine the best strategy for the tea supply chain, considering experts’ opinions and literature review. Firstly, after the main criteria and sub-criteria were determined, criteria weights were obtained using the SF-PIPRECIA method. Then, using these criteria weights, alternative strategies were ranked using the SF-CODAS method. Fig. 1 shows the flowchart of the research.

3.1. Spherical fuzzy-based decision-making methodology

The proposed methodology integrates the PIPRECIA and CODAS decision-making techniques within a spherical fuzzy environment, comprising two main stages to evaluate and determine the most sustainable strategies for ASCs. In the first stage, the SF-PIPRECIA method assesses and assigns weights to each criterion within the established hierarchical structure. This stage ensures that the importance of each criterion is accurately reflected, considering the inherent uncertainties and vagueness associated with expert judgments. In the second stage, the SF-CODAS method evaluates and ranks the alternative strategies. This approach involves calculating each alternative’s Euclidean and Taxicab distances from the negative ideal solution, thus facilitating a robust comparison of the strategies under consideration. By integrating SF-PIPRECIA and SF-CODAS, the methodology provides a comprehensive framework for addressing the complexity and fuzziness in decision-making processes, ultimately identifying the most sustainable strategy for enhancing ASC resilience and sustainability.

3.2. Preliminaries of spherical fuzzy sets

In traditional fuzzy set theory, the membership function (μ) is used to represent the degree of membership of an element to a set, while the non-membership degree is calculated as 1-μ. However, relying solely on the membership function may not fully capture the inherent fuzziness in some scenarios. Atanassov [84] extended the fuzzy set theory by introducing intuitionistic fuzzy sets (IFSs) to address this limitation. In IFSs, both membership (μ) and non-membership (ν) functions define an element’s relationship to the set, with their values ranging between [0,1]. A third function, hesitancy (π), is introduced, which accounts for the uncertainty or hesitation between the membership and non-membership degrees, ensuring their sum does not exceed 1.

Definition 1: An intuitionistic fuzzy number (IFN) within a fixed set X is represented as $\widetilde{I}$ in Eq. (1). IFNs simplify IFSs and are defined [84]:

$$\widetilde{I} \cong \{x,\ \mu_{\widetilde{I}}(x),\ \nu_{\widetilde{I}}(x); x \in X\} \tag{1}$$

where $\mu_{\widetilde{I}}(x)$ and $\nu_{\widetilde{I}}(x)$ indicate the membership and non-membership degrees of the element $x \in X$ to $\widetilde{I}$. Their sum must not exceed 1. The degree of hesitancy is calculated as.

$$\pi_{\widetilde{I}}(x) = 1 - \mu_{\widetilde{I}}(x) - \nu_{\widetilde{I}}(x) \tag{2}$$

Picture fuzzy sets (PiFS), introduced by Cuong and Kreinovich [85], expand on intuitionistic fuzzy sets by allowing for a broader range of responses, particularly useful in contexts such as voting or decision-making, where multiple responses (e.g., yes, no, abstain, reject) are possible. While traditional IFSs are limited in situations where decision-makers might express multiple probabilities, PiFSs provide a more refined way to capture decision-makers’ evaluations [86]. This method is particularly effective when faced with four possible responses: support, oppose, neutral, or refusal [87].

Definition 2. A PiFs on a $\widetilde{A}_p$ in the universe of discourse U is defined by Cuong and Kreinovich [85],

$$\widetilde{A}_p = \left\{ \left\langle u, \left(\mu_{\widetilde{A}_p}(u), I_{\widetilde{A}_p}(u), \nu_{\widetilde{A}_p}(u)\right) \middle| u \in U \right\} \right. \tag{3}$$

Summation of $\mu_{\widetilde{A}_p}(u), I_{\widetilde{A}_p}(u), \nu_{\widetilde{A}_p}(u)]$ cannot exceed 1. For each element u, these values represent membership, indeterminacy, and non-membership degrees, respectively. The refusal degree is calculated as.

$$\chi_{\widetilde{A}_p} = 1 - \left(\mu_{\widetilde{A}_p}(u) + \nu_{\widetilde{A}_p}(u) + I_{\widetilde{A}_p}(u)\right) \tag{4}$$

Mahmood et al. [88] introduced the concept of spherical fuzzy sets (SFS) and T-spherical fuzzy sets (T-SFS) as a generalization of fuzzy sets, intuitionistic fuzzy sets, and Pythagorean fuzzy sets. Gündoğdu and Kahraman contributed to the literature by further developing definitions of SFSs and applying them to decision-making problems [89]. SFSs are characterized by functions defined on a spherical surface, with the parameters of these functions independently specified within a broader domain [90]. Similar to intuitionistic, Pythagorean, and neutrosophic fuzzy sets, spherical fuzzy numbers (SFNs) are defined using three parameters [91]. These parameters are allocated on a spherical surface, providing a more generalized framework for fuzzy sets. This generalization offers decision-makers greater flexibility in modeling information’s inherent ambiguity and uncertainty. By enabling a more

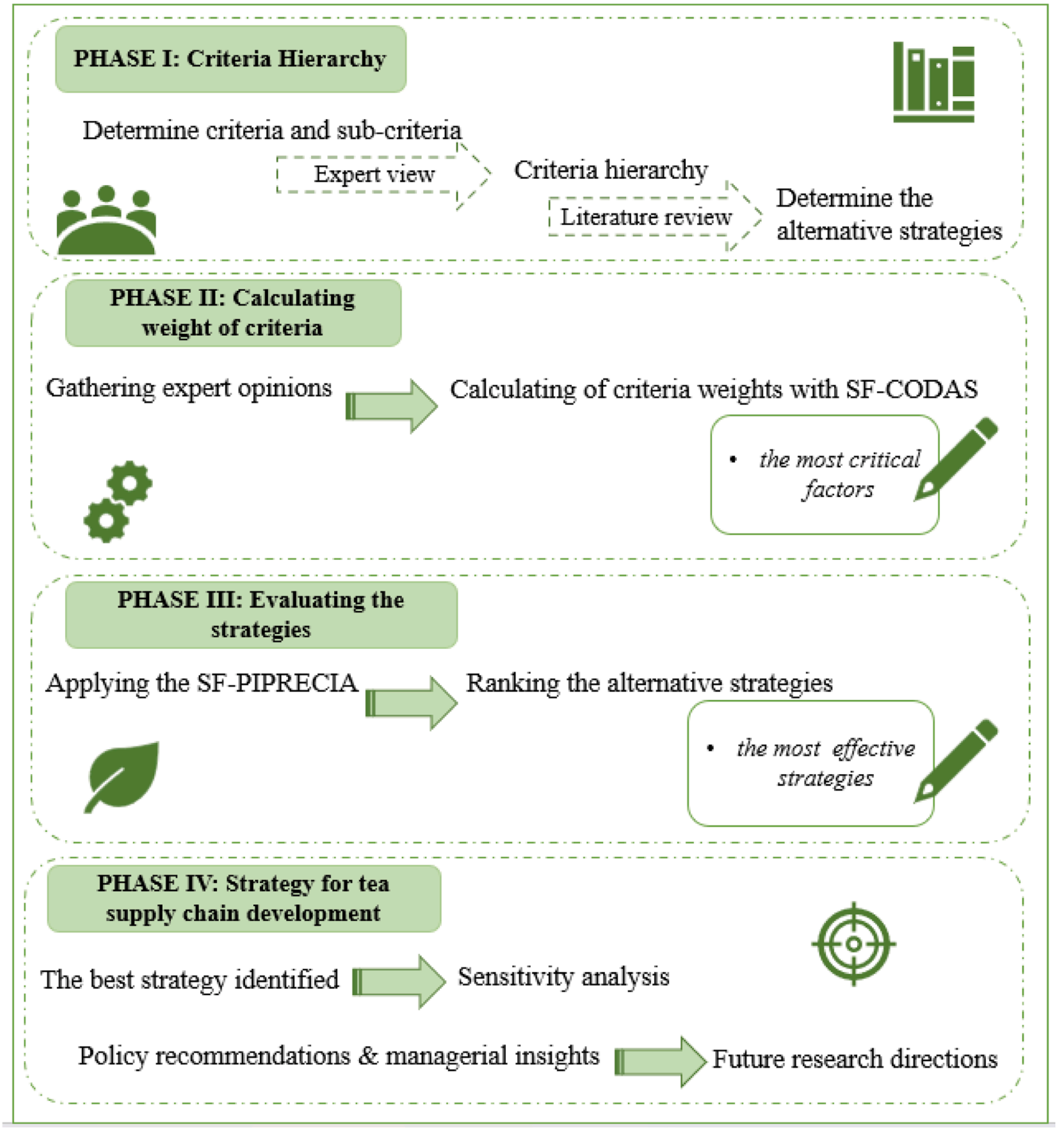

Fig. 1. Flowchart of the study.

comprehensive representation of uncertainty, SFSs enhance the precision and robustness of decision-making processes, making them particularly valuable in complex and uncertain environments such as those encountered in sustainability assessments and supply chain management.

Definition 3: A SFN $\widetilde{S}$ is presented in a fixed set X [89]:

$$\widetilde{\mathrm{S}} \cong \ \{\mathrm{x},\ \widetilde{\mathrm{S}}(\mu_{\tilde{\mathrm{s}}}(\mathrm{x}),\ \mathrm{v}_{\tilde{\mathrm{s}}}(\mathrm{x}),\ \pi_{\tilde{\mathrm{s}}}(\mathrm{x}));\mathrm{x}\in \mathrm{X}\} \tag{5}$$

$\mu_{\tilde{\mathrm{s}}}(\mathrm{x}) : \mathrm{X} \mapsto [0,\ 1]$, $\mathrm{v}_{\tilde{\mathrm{s}}}(\mathrm{x}) : \mathrm{X} \mapsto [0, 1]$ and $\pi_{\tilde{\mathrm{s}}}(\mathrm{x}) : \mathrm{X} \mapsto [0, 1]$ define the membership function, non-membership function, and hesitancy function of the element $\mathrm{x} \in \mathrm{X}$ to $\widetilde{\mathrm{S}}$.

The primary difference between SFSs and other types of fuzzy sets lies in the treatment of hesitancy. In SFSs, the degree of hesitancy can reach a maximum value of 1. Additionally, the squared sum of the three functions falls within the range of 0 to 1, and each function is independently defined within the interval [0,1].

$$0 \le \mu_{\tilde{\mathrm{s}}}(\mathrm{x})^2 + \mathrm{v}_{\tilde{\mathrm{s}}}(\mathrm{x})^2 + \pi_{\tilde{\mathrm{s}}}(\mathrm{x})^2 \le 1; \mathrm{x}\ \in \mathrm{U} \tag{6}$$

Let $\widetilde{\alpha} = \mathrm{S}\ (\mu_{\tilde{\alpha}},\ \mathrm{v}_{\tilde{\alpha}},\ \pi_{\tilde{\alpha}})$ and $\widetilde{\beta} = \mathrm{S}\ (\mu_{\tilde{\beta}},\ \mathrm{v}_{\tilde{\beta}},\ \pi_{\tilde{\beta}})$ are two SFNs.

Definition 4: Summation and multiplication operations are given [92]:

$$\widetilde{\alpha} \oplus \widetilde{\beta} = \widetilde{S}\left(\sqrt{\mu_{\tilde{\alpha}}^2 + \mu_{\tilde{\beta}}^2 - \mu_{\tilde{\alpha}}^2\mu_{\tilde{\beta}}^2},\ \ v_{\tilde{\alpha}}v_{\tilde{\beta},}\ \sqrt{\left(1-\mu_{\tilde{\alpha}}^2\right)\pi_{\tilde{\beta}}^2 + \left(1-\mu_{\tilde{\beta}}^2\right)\pi_{\tilde{\alpha}}^2 - \pi_{\tilde{\alpha}}^2\pi_{\tilde{\beta}}^2}\right) \tag{7}$$

$$\widetilde{\alpha} \otimes \widetilde{\beta} = \widetilde{S}\left(\mu_{\tilde{\alpha}}\mu_{\tilde{\beta},}\ \sqrt{v_{\tilde{\alpha}}^2 + v_{\tilde{\beta}}^2 - v_{\tilde{\alpha}}^2 v_{\tilde{\beta}}^2},\sqrt{\left(1-v_{\tilde{\alpha}}^2\right)\pi_{\tilde{\beta}}^2 + \left(1-v_{\tilde{\beta}}^2\right)\pi_{\tilde{\alpha}}^2 - \pi_{\tilde{\alpha}}^2\pi_{\tilde{\beta}}^2}\ \right) \tag{8}$$

Definition 5: $\widetilde{\alpha}$ is multiplied by a scalar $(\lambda > 0)$ [93]:

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

Definition 6: The power $(\lambda > 0)$ of $\widetilde{\alpha}$ [89]:

$$\widetilde{\alpha}^{\lambda} = \widetilde{S}\left(\mu_{\tilde{\alpha}}^{\lambda},\ \sqrt{1-\left(1-v_{\tilde{\alpha}}^2\right)^{\lambda}},\ \sqrt{\left(1-v_{\tilde{\alpha}}^2\right)^{\lambda} - \left(1-v_{\tilde{\alpha}}^2-\pi_{\tilde{\alpha}}^2\right)^{\lambda}}\right) \tag{10}$$

Definition 7: Score function of $\widetilde{\alpha}$ [94].

$$S(\widetilde{\alpha}) = \frac{1}{3}\left(2+\mu_{\tilde{\alpha}}^2 - v_{\tilde{\alpha}}^2 - \pi_{\tilde{\alpha}}^2\right) \tag{11}$$

Definition 8: Spherical Weighted Arithmetic Mean (SWAM) operator [95]:

$$\mathrm{SWAM}_w(\widetilde{A}_{s_1},\widetilde{A}_{s_2},\ldots,\widetilde{A}_{s_n}) = \left\{\left[1-\prod\nolimits_{i=1}^{n}\left(1-\mu_{\widetilde{A}_s}^2\right)^{w_i}\right]^{1/2},\right.$$
$$\left.\prod\nolimits_{i=1}^{n}\nu_{\widetilde{A}_s}^{w_i},\left[\prod\nolimits_{i=1}^{n}\left(1-\mu_{\widetilde{A}_s}^2\right)^{w_i}-\prod\nolimits_{i=1}^{n}\left(1-\mu_{\widetilde{A}_s}^2-\pi_{\widetilde{A}_s}^2\right)^{w_i}\right]^{1/2}\right\} \tag{12}$$

where $w = (w_1, w_2, \ldots, w_n); w_i \in [0,1]; \sum_{i=1}^{n} w_i = 1$

3.3. Spherical fuzzy PIPRECIA

This study introduces the SF-PIPRECIA method to the literature. This innovative approach is designed to assign weights to criteria specifically for assessing the sustainability of ASC. However, its potential applications extend to various complex decision-making scenarios. The SF-PIPRECIA method provides a robust framework for evaluating and prioritizing various criteria under uncertainty. The following steps detail the process of the SF-PIPRECIA method:

Step 1.1. A decision matrix is created by gathering expert evaluations for each criterion using linguistic terms (Table 4). Initially, criteria are ranked without considering their importance. Experts then use linguistic terms to assess the relative importance of each criterion, starting with the second one. Each evaluation $L_{it} = (\mu_{it}, \nu_{it}, \pi_{it})$ by expert t for criterion j is represented as a fuzzy number.

Step 1.2. Opinions from experts are aggregated via the SWAM operator.

Step 1.3. The score values of each aggregated evaluation are calculated.

Step 1.4. The coefficient is determined.

$$k_j = \begin{cases} = 1 & \text{if } j = 1 \\ 2 - S(\widetilde{Y}_j) & \text{if } j > 1 \end{cases} \tag{13}$$

Step 1.5. Unnormalized weight is calculated.

$$q_j = \begin{cases} = 1 & \text{if } j = 1 \\ \dfrac{q_j - 1}{k_j} & \text{if } j > 1 \end{cases} \tag{14}$$

Step 1.6. The normalized criteria weights are determined.

$$w_j'' = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{15}$$

Let n is criteria number.

Step 2.1 The subsequent steps entail applying the inverse approach of the SF-PIPRECIA method. Initially, experts evaluate the criteria using the linguistic terms provided in Table 4, utilizing a pairwise comparison technique. Unlike traditional methods that start with the first criterion, this approach begins with the penultimate criterion. This reverse sequencing aims to mitigate potential biases and improve the accuracy of the relative importance assessments.

Step 2.2. Opinions from experts are aggregated via the SWAM operator.

Step 2.3. The score values of each aggregated evaluation are calculated.

Table 4
Importance evaluations of criteria.

Linguistic Term	μ, ν, π
AL-Absolutely Low Important	0.10, 0.970, 0.00
VL-Very Low Important	0.20, 0.80, 0.10
L-Low Important	0.30, 0.70, 0.20
ML-Medium Low Important	0.40, 0.60, 0.30
EE-Equal Important	0.50, 0.50, 0.40
MH-Medium High Important	0.60, 0.40, 0.30
H-High Important	0.70, 0.30, 0.20
VH-Very High Important	0.80, 0.20, 0.10
AH-Absolutely High Important	0.9, 0.10, 0.00

Step 2.4. The coefficient is determined.

$$k'_j = \begin{cases} = 1 & \text{if } j = \mathrm{n} \\ 2 - S(\widetilde{Y}_j) & \text{if } j < 1 \end{cases} \tag{16}$$

Step 2.5. Unnormalized weights are obtained.

$$\mathrm{q}'_j = \begin{cases} = 1 & \text{if } j = \mathrm{n} \\ \dfrac{\mathrm{q}'_{j+1}}{k'_j} & \text{if } j < \mathrm{n} \end{cases} \tag{17}$$

Step 2.6. The normalized criteria weights are calculated.

$$w'_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{18}$$

Step 3. The criteria weights are obtained.

$$w_j = \frac{w''_j + w'_j}{2} \tag{19}$$

3.4. Spherical fuzzy CODAS

The CODAS method, introduced by Ghorabaee et al. in [96], assesses alternatives based on their distance from the negative ideal solution. It uses two distance measures: Euclidean and Taxicab (Manhattan). The primary measure, Euclidean distance, determines how far alternatives are from the negative ideal. In contrast, the secondary measure, Taxicab distance, addresses cases where alternatives are similar or nearly equal in Euclidean distance. Alternatives are first evaluated using the Euclidean (l2-norm) distance, and if they remain indistinguishable, the Taxicab (l1-norm) distance is used. The alternative farthest from the negative ideal solution is deemed the best. However, since these distances are defined with crisp numbers, they may not be suitable in fuzzy environments. To address this, fuzzy weighted Hamming Euclidean distances can be used. This article contributes by allowing the use of SFSs for membership, non-membership, and hesitancy functions in the CODAS method. The steps for SF-CODAS are outlined below [97]:

Step 1. Assume that decision-makers construct the decision and benchmarking matrices using the linguistic variables outlined in Table 5. In this context, $\widetilde{X}_{ij}^{k}$ represents the evaluation. The alternatives are selected based on specific criteria denoted by the decision matrix K, which is formulated using linguistic terms. When assessing the alternative locations, all criteria are considered benefit criteria, meaning that a higher value for any criterion indicates a better option.

Step 2. The linguistic variables identified in Step 1 are translated into SFNs according to Table 5, and the fuzzy decision matrix is subsequently formed.

Step 3. The experts' opinions are combined, considering the weight assigned to each one. Subsequently, the aggregated decision matrix is obtained using the SWAM operator. $\widetilde{\mathrm{X}}_{ij}$ is the aggregated evaluation of alternative i concerning criterion j.

Step 4. The crisp value of each SFN for the aggregated evaluation matrix is determined via the score function. X_{ij} is the crisp value of $\widetilde{\mathrm{X}}_{ij}$.

Step 5. The weighted decision matrix is calculated.

$$u_{ij} = w_j X_{ij} \tag{20}$$

Table 5
Linguistic terms to evaluate the alternatives.

Linguistic Term	μ	ν	π
EL-Extremely Low	0.1	0.9	0.1
VL-Very Low	0.2	0.8	0.2
L-Low	0.3	0.7	0.3
F-Fair	0.5	0.5	0.5
H-High	0.7	0.3	0.3
VH-Very High	0.8	0.2	0.2
EH-Extremely High	0.9	0.1	0.1

where w_j is the weight of the criteria.

Step 6. The negative ideal solution is determined for each criterion.

$$nh_j = \min_j u_{ij} \tag{21}$$

Step 7. Euclidean and Taxicab distances are calculated for each alternative from negative ideal solutions.

$$E_i = \sqrt{\sum_{j=1}^{n} \left(u_{ij} - nh_j\right)^2} \tag{22}$$

$$T_i = \sqrt{\sum\nolimits_{j=1}^{n} \left|u_{ij} - nh_j\right|} \tag{23}$$

Step 8. The relative assessment matrix is formed based on distances.

$$Ra = \left[h_{ip}\right]_{n\times n} \tag{24}$$

$$h_{ip} = \left(E_i - E_p\right) + \left(\psi\left(E_i - E_p\right) \times \left(T_i - \mathrm{p}\right)\right) \tag{25}$$

m is the number of alternatives and $p \in \{1, 2, \ldots, m\}$. The function ψ acts as a threshold to identify when the Euclidean distances of two alternatives are equal.

$$\psi(x) = \begin{cases} 1| \text{ if } |x| \geq \tau \\ 0| \text{ if } |x| < \tau \end{cases} \tag{26}$$

The threshold parameter τ is set by decision-makers. If the Euclidean distance between two alternatives is less than τ, the alternatives are then compared using the Taxicab distance.

Step 9. The evaluation score of each alternative is determined.

$$H_i = \sum_{p=1}^{n} h_{ip} \tag{27}$$

Step 10. Alternatives are ranked in descending order according to their evaluation scores, with the highest value indicating the best alternative.

4. Case study

The ASC is a critical sector in Turkey that contributes significantly to the national economy. Tea is culturally and economically important among the various agricultural products. Türkiye is one of the largest tea producers in the world, and the sustainability of its tea supply chain has become increasingly important due to growing concerns about environmental impact, resource depletion, and social equity. Challenges such as inefficient resource management, high energy consumption, and inadequate implementation of sustainable agricultural practices plague current practices in the agri-food sector, including the tea industry. These challenges highlight the urgent need for effective strategies to improve sustainability in the sector.

This study focuses on developing a sustainability model tailored to the ASCs in Turkey, with a specific application to the tea industry. The proposed methodology, which integrates spherical fuzzy PIPRECIA with CODAS, is particularly suited to address the complexities and uncertainties inherent in the sector. By applying this methodology, the study aims to identify the most sustainable strategies for the tea industry, thus bridging existing research gaps in sustainability assessment within ASCs. The model addresses environmental concerns and social and economic factors, providing a holistic approach to sustainability. This case study thus represents a meaningful application of the proposed methodology, demonstrating its usefulness in addressing real-world challenges faced by the Turkish agri-food sector.

This study aims to determine the best sustainable strategy for the tea supply chain. For this purpose, we determined four main criteria and 49 sub-criteria in the sustainability perspective, as described in Table 6. The determination of criteria in this study followed a structured process to ensure a comprehensive and relevant evaluation of the ASC sustainability, particularly within the tea industry in Türkiye. The criteria selection is based on an extensive literature review, industry reports, and expert consultations. Key sustainability factors commonly addressed in agri-food sectors, such as environmental impact, economic viability, social responsibility, and technological advancement, were considered. To refine the criteria, input from industry professionals and stakeholders is sought to ensure alignment with real-world challenges and

Table 6
Main criteria and sub-criteria.

Main criteria	Sub-criteria	Refs.
Environmental	**Group 1: Resource Utilization**	
	High water consumption (C_1)	[30,34]
	High energy consumption (C_2)	[30]
	Using renewable energy (C_3)	[30,34]
	Low-capacity utilization (C_4)	[98]
	Using recycled materials (C_5)	[30,31]
	Energy scarcity (C_6)	[99]
	Group 2: Pollution	
	High pollution generation (C_7)	[30,33]
	Odor and dust disruption to the community (C_8)	[100]
	Climate change mitigation (C_9)	[101]
	Biodiversity conservation (C_{10})	[101]
	Impact of extreme weather conditions (C_{11})	[99]
	Carbon footprint (C_{12})	[102]
Social	**Group 3: Community Impact**	
	Lack of community initiatives (C_{13})	[30,101]
	Poor health and safety (C_{14})	[30,103]
	Social equity (C_{15})	[101]
	Poor social acceptance (C_{16})	[101]
	Low contribution to regional development (C_{17})	[101]
	Low community engagement (C_{18})	[101]
	Group 4: Efficiency	
	Regulatory non-compliance (C_{19})	[98]
	Low labor competency (C_{20})	(Asrol et al. 2024)
	Low flexibility (C_{21})	[33]
	Poor mobility and accessibility (C_{22})	[104,105]
	Group 5: Employment and Labor Conditions	
	Unemployment for local labor (C_{23})	(Asrol et al. 2024)
	Weak stakeholder partnership (C_{24})	[101]
	Low employee satisfaction (C_{25})	[106]
	Unfair profit allocation (C_{26})	[101]
	Non-compliance with corporate social responsibility (C_{27})	[98]
Financial	**Group 6: Economic**	
	Insufficient investments (C_{28})	[30,24]
	Low employment opportunities (C_{29})	[30,104]
	Low supply chain competitiveness (C_{30})	[30,98]
	High employment requirement (C_{31})	[30,107]
	Financial instability (C_{32})	[99]
	Group 7: Market	
	Low service capability (C_{33})	[104]
	Low market competitiveness (C_{34})	[98]
	Inefficient value chain (C_{35})	[101]
	High production loss (C_{36})	[100]
	Gap to reference price (C_{37})	[108]
	Low consumer satisfaction (C_{38})	[106]
Technical	**Group 8. Operational**	
	Transportation failures and delays (C_{39})	[99]
	Demand volatility (C_{40})	[99]
	Unavailability of machinery and tools (C_{41})	[107]
	Inefficient material usage (C_{42})	[109]
	Low product diversity (C_{43})	Expert view
	Group 9: Technological Advancements	
	Weak IT integration (C_{44})	[110]
	Limited automation and robotics usage (C_{45})	Expert view
	Low precision agriculture adoption (C_{46})	[107]
	Lag in digitalization (C_{47})	Expert view
	Cybersecurity threats (C_{48})	[101]
	Low innovation and R&D investment (C_{49})	Expert view

Table 7
Information about the expert group.

	Experience	Education	Job Title	Research area
E1	10 years	PhD	Academician	Risk Assessment
E2	40 years	Master's	Farmer	-
E3	16 years	PhD	Academician	Operation Research
E4	14 years	PhD	Academician	Environmental Engineering
E5	15 years	PhD	Academician	Management
E6	8 years	Master's	Manager	-
E7	10 years	PhD	Academician	Agricultural Engineering
E8	12 years	PhD	Academician	Biology

opportunities specific to the tea industry. We used the SF-PIPRECIA method to calculate the criteria weights.

The alternatives were developed by identifying actionable strategies to enhance sustainability within the supply chain. These strategies were grounded in empirical evidence and reflected the key trends and innovations driving sustainability efforts in similar industries. The chosen alternatives—adopting digital technologies, establishing buyer-supplier partnerships, enhancing regulatory and environmental support, investing in sustainable proficiency and skill development, and diversifying supply chains geographically—represent practical, high-impact solutions. Each alternative was validated through expert judgment to ensure its applicability and potential effectiveness in addressing the identified sustainability criteria. The ranks of alternative strategies were calculated by integrating the criteria weights obtained with SF-PIPRECIA into the SF-CODAS method.

4.1. *Strategies for sustainable supply chain*

To meet social expectations, businesses turn to actions that create better environmental, economic, and social impacts. Thus, they act in line with their and society's interests by managing and improving these factors throughout the supply chain [99]. Although sustainable approaches are important in the supply chain, many barriers exist. Strategies should be developed to overcome these barriers. The strategies selected for this study are chosen based on their critical relevance to improving the sustainability of the ASCs, particularly in Türkiye's tea industry. Each strategy addresses a distinct aspect of sustainability and has been supported by empirical evidence, industry reports, or prior research findings, making them highly appropriate for this analysis. Sustainable strategies help organizations deal with sustainability issues in production processes and supply chains [111]. For this purpose, we defined five different strategies based on literature review and expert opinions. Alternative strategies are as follows:

S1. *Adopt Digital Technologies:* Implement advanced agricultural technologies such as IoT, AI, and data analytics to optimize resource use (water, energy), monitor environmental impacts (pollution, carbon footprint), and enhance operational efficiency (market competitiveness, supply chain performance) [99]. Digital technologies are vital in enhancing efficiency and transparency throughout the supply chain. By adopting innovations such as blockchain, IoT, and AI, companies can monitor and optimize operations in real-time, reduce waste, and improve traceability. Digital technologies have significantly improved supply chain performance and sustainability across various sectors, including agriculture.

S2. *Establish Buyer-Supplier Partnerships:* Foster collaborative relationships with suppliers and buyers to promote sustainable practices throughout the supply chain. This includes joint initiatives for resource efficiency, waste reduction, and sustainable materials sourcing [111]. Strengthening partnerships between buyers and suppliers ensures a stable and resilient supply chain. Empirical studies show that close collaboration leads to better resource management, shared sustainability practices, and increased trust, which is essential for addressing the volatility in agricultural production.

S3. *Enhance Regulatory and Environmental Support:* Supply chain stakeholders should collaborate to both develop and enforce comprehensive administrative policies and environmental regulations that promote sustainable practices while simultaneously advocating for enhanced government support and incentives [112]. Regulatory frameworks and environmental policies play a crucial role in shaping sustainable practices within the industry. Prior research has shown that strong regulatory support and environmental incentives can drive organizations to adopt eco-friendly practices, ensuring that production processes align with sustainability goals.

S4. *Invest in Sustainable Proficiency and Skill Development:* Provide ongoing training and education programs for employees to enhance their skills in sustainable agricultural practices. This includes training on efficient resource use, biodiversity conservation, and compliance with environmental regulations [111]. Human capital is one of the key drivers of sustainability, particularly in industries like agriculture, where skill gaps can hinder the adoption of sustainable practices. By investing in education and skill development, companies can equip their workforce with the knowledge needed to implement sustainable techniques. Sustainable proficiency training leads to greater environmental performance and long-term viability in supply chains.

S5. *Diversify Supply Chain Geographically:* Expand the geographical scope of the supply chain to reduce risks associated with climate change impacts, such as extreme weather conditions and resource scarcity. Diversification can also enhance resilience against market fluctuations and geopolitical risks [99]. Geographic diversification is crucial for mitigating climate change, natural disasters, and geopolitical issues that could disrupt the supply chain. Diversifying production and sourcing locations reduces vulnerability and improves overall sustainability by balancing resource use and managing environmental impact across regions.

4.2. *Expert group*

In this study, eight experts—E1, E2, E3, E4, E5, E6, E7, E8—who knowledge in relevant fields, are collected. Six of these experts had previously worked in the tea industry. Expert evaluations are gathered to determine criteria, importance levels, and alternative strategies with the literature review within a hierarchical structure. Table 7 suggests detailed information about the expert group.

4.3. *Calculation of criteria weights with SF-PIPRECIA*

In this study, the determination of criterion weights and the ranking of alternative strategies are made with the opinions of eight experts.

First, experts evaluate the main criteria and then the sub-criteria based on each main criterion using the linguistic terms in Table 4. The

Table 8
Expert opinions for main criteria.

SF-PIPRECIA									SF-PIPRECIA INVERSE								
	E1	E2	E3	E4	E5	E6	E7	E8		E1	E2	E3	E4	E5	E6	E7	E8
Environmental									**Technical**								
Social	L	VL	VL	L	L	AL	L	MH	**Financial**	EE	MH	MH	MH	L	VL	H	MH
Financial	VL	ML	H	EE	MH	VL	H	ML	**Social**	MH	L	L	EE	L	VH	L	H
Technical	VL	L	VL	ML	H	VH	ML	L	**Environmental**	H	H	VH	H	H	AH	VH	H

Table 9
SF-PIPRECIA calculations for main criteria.

	Aggregated Evaluations			Score	k_j	q_j	w''_j
	μ	ν	π				
Environmental					1.000	1.000	0.394
Social	0.329	0.696	0.196	0.528	1.472	0.679	0.268
Financial	0.519	0.569	0.264	0.625	1.375	0.494	0.195
Technical	0.501	0.555	0.202	0.634	1.366	0.362	0.143

Table 10
SF-PIPRECIA INVERSE calculations for main criteria.

	Aggregated Evaluations			Score	k_j	q_j	w'_j
	μ	ν	π				
Environmental					1.000	1.000	0.358
Social	0.550	0.495	0.284	0.659	1.341	0.746	0.267
Financial	0.544	0.449	0.240	0.679	1.321	0.565	0.202
Technical	0.766	0.249	0.153	0.834	1.166	0.484	0.173

experts' evaluations of the main criteria are summarized in Table 8. Based on Table 4, the linguistic terms are converted to SFNs.

Then, the SWAM operator (see Definition 8) is applied to aggregate expert opinions. It is assumed that all experts have the same weight. In the first phase of the methodology, the SF-PIPRECIA part of Table 7 is used. Aggregated expert opinions are presented in Table 9 for the main criteria. The score values are calculated via Eq. (8). The coefficient, unnormalized weight, and normalized weight for each main criterion are determined based on Eq. (13), Eq. (14), and Eq. (15), respectively, as given in Table 9.

Then, the inverse phase of the methodology is calculated. For this aim, the SF-PIPRECIA INVERSE part of the Table is used. Aggregated expert opinions are presented in Table 10 for the main criteria. The score values are calculated via Eq. (8). The coefficient, unnormalized weight, and normalized weight for each main criterion are determined based on Eq. (16), Eq. (17), and Eq. (18), respectively, as given in Table 10.

Then Eq. (19) is applied, and the weights of the main criteria are calculated, as shown in Fig. 2.

The weights of the main criteria of "Environmental, Technical, Social and Financial" are 0.284, 0.250, 0.235 and 0.231, respectively, as exposed in Fig. 2. The most important main criterion is “Environmental,” with a weight of 0.284. Moreover, "Financial" is the least important criterion, with 0.231.

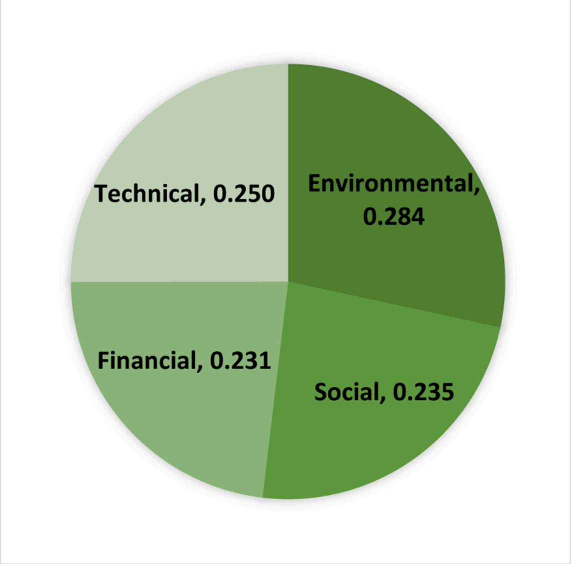

Fig. 2. Main criteria weights.

According to the results, the weights obtained for the main criteria with the SF-PIPRECIA method illustrate that the most important factors to be considered in sustainable ASC management strategy selection are environmental and technical. Environmental factors certainly come to the fore when we consider today's conditions, and consumers are conscious of the expectations of the sustainability framework. In addition, technical factors are expected to be at the forefront when considering sustainable SCM. The least important factor was determined by experts to be financial. However, it is realized that the criteria weights are very close.

The same group of experts is consulted to assess the sub-criteria for each main criterion, using pairwise comparisons as outlined in Appendix (Table A1). The steps of the SF-PIPRECIA method are followed to determine the local weights of the sub-criteria. The final weights for the sub-criteria are calculated by multiplying the weights of the main criteria with the corresponding sub-criteria weights, as shown in Table 11. This table's "In-Criteria Rank” column shows sub-criteria rankings based on the same main criterion.

According to Table 9, “Carbon footprint (C12)”, “High water consumption (C1)” “Low innovation and R&D investment (C49)”, “Transportation failures and delays (C39)”, “Insufficient investments (C28)” are the most important criteria with weights of 0.0416, 0.0405, 0.0347, 0.0347. Table 8 illustrates that sub-criteria related to the environmental criterion have priority. In particular, in pairwise comparisons, 62.5% of experts stated that the “Carbon footprint (C12)” criterion has higher importance than other criteria (see Appendix). According to the "In-Criteria Rank" column regarding the sub-criteria of environmental main criterion, the most critical sub-criteria are linked to high water and energy consumption after carbon footprint. Furthermore, the “Energy scarcity (C6)” criterion is the least important, with a weight of 0.0146.

4.4. Ranking alternative strategies with SF-CODAS

The tea supply chain is of significant importance to Türkiye, both economically and culturally. Türkiye is one of the largest tea producers in the world, within the Black Sea region, particularly Rize, being the primary cultivation area. In Türkiye, tea production is concentrated in the northeastern Black Sea region. The tea plantations are spread across Artvin, Rize, Trabzon, Ordu, and Giresun, as shown in Fig. 3. The tea industry supports the livelihoods of thousands of farmers and contributes substantially to the country's GDP. According to the Turkish Statistical Institute, tea production in Türkiye reached over 260,000 tons in 2021, underscoring its critical role in the agricultural sector [113]. Moreover, tea is an integral part of Turkish culture and daily life, with the country having one of the highest per capita tea consumption rates globally [114]. Therefore, sustainability in the tea supply chain is

Table 11
Sub-criteria weights.

Main Criteria	Sub-Criteria	Local Weight	Final Weight	Global Rank	In-Criteria Rank
Environmental	High water consumption (C_{1})	0.1428	0.0405	2	2
	High energy consumption (C_{2})	0.1039	0.0295	9	3
	Using renewable energy (C_{3})	0.0839	0.0238	17	5
	Low-capacity utilization (C_{4})	0.0614	0.0174	27	8
	Using recycled materials (C_{5})	0.0561	0.0159	30	9
	Energy scarcity (C_{6})	0.0516	0.0146	38	12
	High pollution generation (C_{7})	0.0535	0.0152	37	11
	Odor and dust disruption to the community (C_{8})	0.0537	0.0152	36	10
	Climate change mitigation (C_{9})	0.0645	0.0183	25	7
	Biodiversity conservation (C_{10})	0.0785	0.0223	19	6
	Impact of extreme weather conditions (C_{11})	0.1033	0.0293	10	4
	Carbon footprint (C_{12})	0.1467	0.0416	1	1
Social	Lack of community initiatives (C_{13})	0.1314	0.0309	8	2
	Poor health and safety (C_{14})	0.1109	0.0261	13	3
	Social equity (C_{15})	0.0783	0.0184	24	5
	Poor social acceptance (C_{16})	0.0585	0.0137	41	7
	Low contribution to regional development (C_{17})	0.0474	0.0111	43	9
	Low community engagement (C_{18})	0.0368	0,0087	45	11
	Regulatory non-compliance (C_{19})	0,0321	0,0075	47	13
	Low labor competency (C_{20})	0,0294	0,0069	49	15
	Low flexibility (C_{21})	0,0307	0,0072	48	14
	Poor mobility and accessibility (C_{22})	0,0346	0,0081	46	12
	Unemployment for local labor (C_{23})	0,0454	0,0107	44	10
	Weak stakeholder partnership (C_{24})	0,0547	0,0129	42	8
	Low employee satisfaction (C_{25})	0,0738	0,0173	28	6
	Unfair profit allocation (C_{26})	0,1034	0,0243	15	4
	Non-compliance with corporate social responsibility (C_{27})	0,1325	0,0311	7	1
Financial	Insufficient investments (C_{28})	0,1462	0,0337	5	1
	Low employment opportunities (C_{29})	0,1037	0,0240	16	4
	Low supply chain competitiveness (C_{30})	0,0810	0,0187	22	6
	High employment requirement (C_{31})	0,0681	0,0157	31	8
	Financial instability (C_{32})	0,0676	0,0156	34	9
	Low service capability (C_{33})	0,0620	0,0143	40	11
	Low market competitiveness (C_{34})	0,0632	0,0146	39	10
	Inefficient value chain (C_{35})	0,0707	0,0163	29	7
	High production loss (C_{36})	0,0878	0,0203	21	5
	Gap to reference price (C_{37})	0,1090	0,0252	14	3
	Low consumer satisfaction (C_{38})	0,1408	0,0325	6	2
Technical	Transportation failures and delays (C_{39})	0,1385	0,0347	4	2
	Demand volatility (C_{40})	0,1087	0,0272	11	3
	Unavailability of machinery and tools (C_{41})	0,0911	0,0228	18	5
	Inefficient material usage (C_{42})	0,0736	0,0184	23	7
	Low product diversity (C_{43})	0,0624	0,0156	33	10
	Weak IT integration (C_{44})	0,0615	0,0154	35	11
	Limited automation and robotics usage (C_{45})	0,0625	0,0156	32	9
	Low precision agriculture adoption (C_{46})	0,0725	0,0182	26	8
	Lag in digitalization (C_{47})	0,0848	0,0212	20	6
	Cybersecurity threats (C_{48})	0,1055	0,0264	12	4
	Low innovation and R&D investment (C_{49})	0,1388	0,0347	3	1

crucial for economic stability and cultural heritage preservation. Implementing sustainable strategies is essential to address challenges such as resource scarcity, environmental degradation, and social equity, ensuring the long-term viability of the tea industry in Türkiye.

Initially, the alternative strategies specific to the sustainability of Türkiye's tea supply chain are identified, ensuring a comprehensive evaluation of factors such as resource utilization, environmental impact, social implications, and economic stability. Applying the SF-CODAS method to evaluate five alternative strategies for the tea supply chain in Türkiye involves a structured decision-making process that addresses the complexities and uncertainties inherent in tea production. Expert opinions from industry professionals are gathered and represented using SFNs. The alternative strategies are assessed according to the relative importance of the predefined criteria. As illustrated in the Appendix (Tables A2 and A3), the initial step involves creating a decision matrix to evaluate options using linguistic terms.

These evaluations are subsequently converted into SFNs and aggregated via Eq. (12). At this stage, it is assumed that all experts have equal weight. Table 12 presents the aggregated evaluation matrix.

Then, the crisp value of each element in the aggregated evaluation matrix is determined via Eq. (8). The weighted decision matrix is

Fig. 3. The production in Türkiye [115].

calculated via Eq. (20). The criteria weights determined by SF-PIPRECIA are used to obtain the weighted decision matrix. The negative ideal solution is determined for each criterion as given in Eq. (21). Euclidean and Taxicab distances from negative ideal solutions are determined via Eqs. (22) and (23). The distances for each alternative are given in Table 13.

The SF-CODAS methodology is then applied to rank the alternative strategies, considering Euclidean and Taxicab distances from the negative ideal solution. The relative assessment matrix is created using Table 13, following Eqs. (24)–(26), with τ set at 0.002. The relative evaluation matrix is presented in Table 14.

Next, Eq. (27) is applied to determine the final assessment scores. Ultimately, the alternative strategy with the highest score is the optimal choice, as illustrated in Fig. 4.

According to the results, S1 emerges as the most effective option for enhancing the sustainability of the tea supply chain in Türkiye, with a high weight of 0.081. Additionally, S3 presents itself as a strong and viable alternative with 0.071. This strategy was determined as highly important by 62.5% of the experts in terms of “Carbon footprint (C12)”, which was determined as the most critical criterion (see Appendix). Conversely, S2 is identified as the least favorable choice for achieving sustainability within the tea supply chain, with a very low weight of -0.254. Experts evaluated this alternative strategy as having low importance, especially regarding sub-criteria related to the Environmental criterion. This strategy was assessed as low importance by 75% of the experts and medium importance by 25%, particularly regarding the “High water consumption (C1)” criterion, which was determined as the second vital criterion.

This method allows for a robust comparison of strategies, ultimately identifying the most sustainable and effective option to enhance the resilience, efficiency, and overall sustainability of Türkiye’s tea supply chain.

These conclusions underscore the importance of adopting advanced agricultural technologies and fostering regulatory and environmental support to achieve sustainable practices in the tea industry. The superior performance of S1 highlights the critical role of technology in optimizing resource use and minimizing environmental impacts, which are crucial for the long-term sustainability of the tea supply chain. The effectiveness of S3 suggests that regulatory frameworks and incentives also play a significant role, reinforcing the need for comprehensive policy support to encourage sustainable practices. On the other hand, the poor performance of S2 indicates that, while important, buyer-supplier partnerships may only be sufficient to drive substantial sustainability improvements with the support of technological advancements and robust regulatory frameworks.

4.5. *Sensitivity analysis*

A sensitivity analysis is conducted in this section to ensure the robustness and stability of the ranking results. This analysis involves generating ten different sets of criteria weights randomly. Each set is used to solve the problem independently, allowing us to observe how changes in criteria weights affect the ranking of alternative strategies. The randomly generated sets of criteria weights are presented in Table 15.

Subsequently, the ranking results derived from these sets are illustrated in Fig. 5. This sensitivity analysis provides valuable insights into the reliability of the proposed methodology. By examining the variations in the rankings under different weight scenarios, we can assess the consistency and dependability of the findings.

Fig. 5 demonstrates that the rankings of the alternatives are indeed sensitive to the criteria weights. This sensitivity indicates that the model is highly responsive to variations in the assigned weights. Despite this sensitivity, the rankings of the alternatives exhibit a commendable level of stability across different sets of criteria weights. Notably, S1 emerges as the dominant alternative in most sets, except Set-6 and Set-7. This consistent performance of S1 across multiple scenarios suggests that the initial ranking result is robust and reliable. Furthermore, the sensitivity analysis highlights the robustness of the proposed methodology. Even with variations in the criteria weights, S1 consistently ranks as the top alternative, reinforcing its suitability as the best strategy for enhancing the sustainability of the tea supply chain in Türkiye.

4.6. *Comparative analysis*

A comparative analysis was conducted using multiple decision-making methods to strengthen the robustness and comprehensiveness of the proposed approach for strategy selection. The proposed approach was expanded to incorporate spherical fuzzy numbers into TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and

Table 12
Aggregated evaluation matrix.

	S1			S2			S3			S4			S5		
	μ	ν	Π	μ	ν	π	μ	ν	π	μ	ν	π	μ	ν	π
C_1	0.635	0.382	0.314	0.352	0.664	0.368	0.701	0.310	0.298	0.678	0.335	0.276	0.729	0.285	0.267
C_2	0.635	0.382	0.314	0.380	0.637	0.399	0.660	0.352	0.291	0.678	0.335	0.276	0.729	0.285	0.267
C_3	0.695	0.318	0.263	0.562	0.464	0.324	0.753	0.252	0.270	0.738	0.268	0.294	0.612	0.407	0.342
C_4	0.697	0.308	0.324	0.737	0.272	0.305	0.600	0.423	0.336	0.680	0.324	0.337	0.590	0.427	0.374
C_5	0.558	0.472	0.318	0.562	0.464	0.324	0.680	0.324	0.337	0.724	0.282	0.306	0.385	0.627	0.401
C_6	0.612	0.407	0.342	0.517	0.499	0.395	0.658	0.357	0.305	0.717	0.305	0.265	0.605	0.404	0.382
C_7	0.517	0.499	0.395	0.540	0.490	0.373	0.720	0.286	0.262	0.746	0.263	0.246	0.550	0.468	0.366
C_8	0.517	0.499	0.395	0.550	0.468	0.366	0.663	0.352	0.349	0.647	0.365	0.354	0.545	0.476	0.361
C_9	0.687	0.321	0.302	0.531	0.485	0.428	0.742	0.261	0.274	0.646	0.384	0.334	0.732	0.289	0.270
C_{10}	0.542	0.483	0.375	0.547	0.475	0.380	0.753	0.252	0.270	0.664	0.353	0.322	0.757	0.262	0.225
C_{11}	0.481	0.532	0.424	0.500	0.521	0.370	0.670	0.338	0.316	0.669	0.355	0.309	0.716	0.295	0.285
C_{12}	0.658	0.357	0.305	0.605	0.404	0.382	0.753	0.252	0.270	0.738	0.268	0.294	0.742	0.270	0.268
C_{13}	0.470	0.550	0.416	0.636	0.381	0.332	0.685	0.327	0.298	0.680	0.336	0.319	0.495	0.519	0.440
C_{14}	0.568	0.460	0.341	0.550	0.468	0.366	0.729	0.285	0.267	0.639	0.382	0.370	0.561	0.457	0.385
C_{15}	0.545	0.476	0.361	0.509	0.514	0.404	0.731	0.280	0.272	0.650	0.360	0.342	0.550	0.468	0.366
C_{16}	0.491	0.536	0.380	0.613	0.406	0.359	0.701	0.310	0.298	0.673	0.345	0.301	0.476	0.541	0.420
C_{17}	0.579	0.431	0.408	0.686	0.325	0.315	0.724	0.282	0.306	0.698	0.304	0.312	0.699	0.314	0.310
C_{18}	0.550	0.468	0.366	0.636	0.381	0.332	0.701	0.310	0.298	0.732	0.276	0.259	0.683	0.330	0.323
C_{19}	0.592	0.413	0.425	0.461	0.555	0.401	0.762	0.246	0.277	0.565	0.440	0.450	0.500	0.510	0.443
C_{20}	0.639	0.368	0.386	0.550	0.468	0.366	0.605	0.404	0.382	0.670	0.338	0.316	0.639	0.368	0.386
C_{21}	0.708	0.301	0.330	0.605	0.412	0.306	0.561	0.457	0.385	0.500	0.521	0.370	0.639	0.376	0.319
C_{22}	0.716	0.295	0.285	0.576	0.445	0.351	0.615	0.400	0.347	0.547	0.475	0.380	0.755	0.257	0.256
C_{23}	0.547	0.475	0.380	0.673	0.338	0.367	0.455	0.564	0.396	0.589	0.428	0.357	0.653	0.360	0.390
C_{24}	0.615	0.400	0.347	0.738	0.268	0.294	0.572	0.453	0.346	0.546	0.467	0.431	0.513	0.508	0.391
C_{25}	0.550	0.468	0.366	0.592	0.421	0.361	0.558	0.472	0.318	0.655	0.363	0.300	0.517	0.499	0.395
C_{26}	0.603	0.418	0.322	0.724	0.282	0.306	0.599	0.425	0.316	0.612	0.407	0.342	0.615	0.400	0.347
C_{27}	0.500	0.510	0.443	0.631	0.391	0.354	0.594	0.426	0.423	0.629	0.379	0.356	0.495	0.519	0.440
C_{28}	0.607	0.426	0.304	0.481	0.532	0.424	0.569	0.459	0.360	0.505	0.535	0.288	0.510	0.515	0.388
C_{29}	0.517	0.499	0.395	0.565	0.449	0.389	0.455	0.564	0.396	0.603	0.418	0.322	0.562	0.455	0.401
C_{30}	0.639	0.376	0.319	0.650	0.360	0.342	0.565	0.449	0.389	0.526	0.503	0.349	0.642	0.375	0.374
C_{31}	0.613	0.406	0.359	0.629	0.379	0.356	0.434	0.589	0.369	0.720	0.286	0.262	0.608	0.414	0.338
C_{32}	0.481	0.532	0.424	0.672	0.334	0.303	0.573	0.451	0.364	0.510	0.515	0.388	0.455	0.564	0.396
C_{33}	0.641	0.363	0.375	0.672	0.334	0.303	0.500	0.510	0.443	0.565	0.449	0.389	0.650	0.360	0.342
C_{34}	0.676	0.339	0.291	0.653	0.368	0.314	0.619	0.408	0.331	0.385	0.627	0.401	0.603	0.409	0.394
C_{35}	0.686	0.325	0.315	0.731	0.280	0.272	0.576	0.445	0.351	0.434	0.589	0.369	0.650	0.360	0.342
C_{36}	0.668	0.342	0.328	0.678	0.340	0.331	0.627	0.392	0.291	0.690	0.327	0.287	0.637	0.395	0.312
C_{37}	0.603	0.409	0.394	0.631	0.391	0.354	0.613	0.406	0.359	0.452	0.573	0.394	0.534	0.479	0.416
C_{38}	0.605	0.404	0.382	0.641	0.363	0.375	0.639	0.376	0.319	0.670	0.338	0.316	0.602	0.411	0.379
C_{39}	0.687	0.322	0.284	0.715	0.285	0.287	0.590	0.427	0.374	0.592	0.421	0.361	0.724	0.282	0.306
C_{40}	0.688	0.333	0.282	0.624	0.390	0.364	0.455	0.564	0.396	0.427	0.599	0.363	0.502	0.532	0.381
C_{41}	0.668	0.342	0.328	0.649	0.361	0.325	0.500	0.521	0.370	0.527	0.504	0.330	0.530	0.487	0.412
C_{42}	0.627	0.384	0.368	0.510	0.505	0.456	0.531	0.495	0.355	0.509	0.514	0.404	0.524	0.500	0.423
C_{43}	0.550	0.468	0.366	0.543	0.483	0.359	0.517	0.499	0.395	0.576	0.436	0.419	0.662	0.341	0.351
C_{44}	0.813	0.191	0.217	0.522	0.512	0.344	0.534	0.479	0.416	0.545	0.476	0.361	0.584	0.440	0.368
C_{45}	0.831	0.171	0.182	0.492	0.537	0.362	0.590	0.427	0.374	0.658	0.357	0.305	0.540	0.490	0.373
C_{46}	0.703	0.306	0.270	0.550	0.468	0.366	0.622	0.404	0.301	0.690	0.329	0.267	0.678	0.340	0.331
C_{47}	0.824	0.183	0.177	0.575	0.438	0.405	0.500	0.521	0.370	0.618	0.395	0.333	0.634	0.388	0.311
C_{48}	0.786	0.217	0.230	0.450	0.574	0.391	0.529	0.497	0.333	0.484	0.547	0.354	0.584	0.440	0.368
C_{49}	0.822	0.182	0.205	0.561	0.457	0.385	0.699	0.314	0.310	0.627	0.384	0.368	0.634	0.388	0.311

Table 13
Distances from negative ideals.

	S1	S2	S3	S4	S5
Euclidean	0.020	0.012	0.019	0.018	0.019
Taxicab	0.310	0.241	0.303	0.298	0.279

Table 14
Relative assessment matrix.

	S1	S2	S3	S4	S5
S1	0.0000	0.0772	0.0007	0.0017	0.0016
S2	-0.0772	0.0000	-0.0694	-0.0630	-0.0444
S3	-0.0007	0.0694	0.0000	0.0010	0.0009
S4	-0.0017	0.0630	-0.0010	0.0000	-0.0001
S5	-0.0016	0.0444	-0.0009	0.0001	0.0000

WISP (Simple Weighted Sum-Product) techniques. This analysis aimed to assess the effectiveness and consistency of the proposed methodology across different methods.

TOPSIS was selected for its capability to evaluate multiple criteria simultaneously and provide an objective ranking of strategies concerning the ideal sustainable solution. Using the SF-TOPSIS (see [116]) for details). technique, the available alternatives were ranked based on the defined criteria. The results in Table 16 revealed that "Adopt Digital Technologies" (S1) was consistently the top choice, while other alternatives exhibited variations in their rankings.

WISP was chosen for its simplicity in prioritizing alternatives and ease of use, thanks to its streamlined normalization process. Additionally, WISP uses four distinct utility measures to evaluate the total usefulness of each alternative, offering a comprehensive framework for decision-making. The results from SF-WISP (see Kara et al. [117] for details), shown in Table 17, also confirmed "Adopt Digital Technologies" (S1) as the best alternative. While the rankings of other alternatives differed, both methods consistently identified the most sustainable strategy, showcasing the reliability and accuracy of the proposed

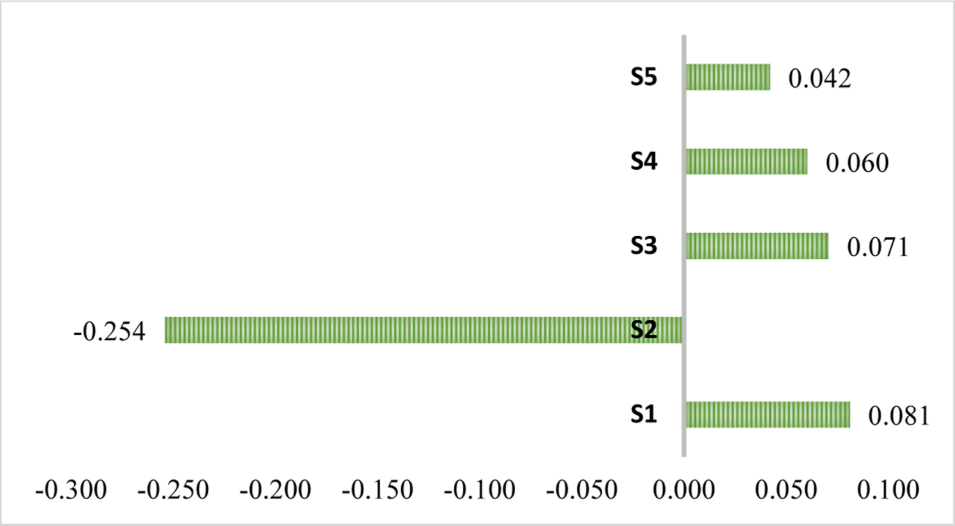

Fig. 4. Final scores of alternative strategies.

spherical fuzzy-based MCDM approach.

The comparative analysis highlights the strength of the proposed methodology when evaluated against SF-TOPSIS and SF-WISP. Fig. 6 visually represents the comparison between these methods, reinforcing the findings.

The comparative analysis reveals a consistent ranking for the top strategy across all three methods, with "Adopt Digital Technologies" (S1) emerging as the best option in each case, highlighting its robust potential for improving the sustainability of the tea supply chain. However, there are slight variations in the rankings of other strategies. For instance, "Enhance Regulatory and Environmental Support" (S3) ranks second in the proposed methodology but is ranked lower in SF-TOPSIS (5th) and SF-WISP (2nd), indicating the proposed method's higher prioritization of regulatory factors. Conversely, "Establish Buyer-Supplier Partnerships" (S2) ranks consistently low, particularly in the proposed methodology and SF-WISP, underscoring its lesser impact on sustainability compared to other strategies. These variations demonstrate how different evaluation methods can influence strategic prioritization, with the proposed methodology showing a stronger focus on regulatory support.

In addition to applying the spherical fuzzy-based MCDM approach, a comprehensive sensitivity analysis is conducted to evaluate the robustness of the results. This analysis examined the stability of the rankings when varying the input data and criteria weights, ensuring that the chosen strategies were not overly sensitive to small fluctuations in these values. Furthermore, a comparative analysis is performed using alternative decision-making techniques to validate the consistency of the findings. The results from both the sensitivity and comparative analyses demonstrate the reliability of the proposed model, thus addressing potential concerns regarding the need for traditional statistical tests, which are not directly applicable to fuzzy logic-based MCDM approaches.

5. Discussion

This study provides scientific results for SSCM for companies in the field of ASC management. In the study, the main criteria, such as environmental, social, financial, and technical importance for SCM, were divided into detailed sub-criteria, and five different strategies were determined based on a literature review and expert opinions. The determined strategies address different aspects of sustainability in the supply chain.

As a result of the SF-PIPRECIA method, “environmental” and “technical” criteria were the most essential main criteria with weights of 0.284 and 0.250, and the least critical main criteria were determined as “financial” with 0.231. Especially for ASC management, considering advances in SCM, more consumer awareness, and the requirements of the sustainability factor, it is expected that the “environmental” criterion will be important. Considering today’s conditions, the “environmental” criterion is critical in tea SCM strategy selection. Most companies in the agri-food sector measure their success in terms of social and environmental factors rather than purely financial terms [118].

Sustainable concentration is achieved by producing more food from the same land while reducing environmental impacts [119]. In addition, the “technical” criterion, which includes transportation situations, digital transformations, and innovation factors, is one of the most important factors to be considered in SCM.

According to the sub-criteria weights, the sub-criteria related to the environmental main criterion also has the highest level of importance. Especially " Carbon footprint (C_{12})" is determined as the most critical sub-criterion with a high weight of 0.0416, and " High water consumption (C_1)" is the second most important criterion with 0.0405, compared to other criteria. In the studies conducted in the field of sustainable supply chains in the last few years, it can be seen that in the environmental dimension, more focus has been placed on carbon emissions [49]. Additionally, among water-dependent activities, agriculture accounts for more than 70% of water consumption worldwide; considering the current water crisis, controlling water consumption is a must for all businesses [48]. Therefore, these criteria should be decisive in selecting the most suitable strategy for ASCMs, especially in industrial factories where environmental impact should be a priority. Because these factories are both affected by the environment and affect the environment. "Low innovation and R&D investment (C_{49})" is selected as another important criterion with a weight of 0.0347.

The least important criterion was " Low labor competency (C_{20})" with a weight of 0.0069. The analysis highlights that social criterion and criteria related to this criterion are less critical in SCM strategy selection for tea supply. This suggests that such factors should not be prioritized in the selection process with a sustainability framework.

As a result of the calculation with the SF-CODAS method, based on the outcomes offered in Fig. 4, the proposed strategies for the tea supply chain are ranked as follows: S1-S3-S4-S5-S2. With a weight of 0.081, “Adopt Digital Technologies (S1)” emerges as the most critical strategy dealing with technological developments in agriculture, such as IoT, AI, and data analytics, to optimize resource use, display environmental impacts, and improve operational productivity. 62.5% of the experts evaluated this strategy as highly important in terms of " Carbon footprint (C12)," which was determined as the most critical criterion (see Appendix). The importance of this strategy for sustainable tea supply chain

Table 15
Weight sets for sensitivity analysis.

	Set-1	Set-2	Set-3	Set-4	Set-5	Set-6	Set-7	Set-8	Set-9	Set-10
$\mathbf{C_{1}}$	0.0324	0.0109	0.0046	0.0174	0.0219	0.0285	0.0315	0.0309	0.0347	0.0119
$\mathbf{C_{2}}$	0.0366	0.0162	0.0336	0.0249	0.0343	0.0232	0.0314	0.0025	0.0230	0.0107
$\mathbf{C_{3}}$	0.0016	0.0203	0.0291	0.0243	0.0317	0.0268	0.0323	0.0093	0.0173	0.0351
$\mathbf{C_{4}}$	0.0244	0.0050	0.0053	0.0372	0.0277	0.0231	0.0321	0.0136	0.0075	0.0389
$\mathbf{C_{5}}$	0.0161	0.0334	0.0374	0.0222	0.0185	0.0005	0.0144	0.0089	0.0278	0.0040
$\mathbf{C_{6}}$	0.0248	0.0302	0.0365	0.0329	0.0244	0.0140	0.0089	0.0156	0.0251	0.0258
$\mathbf{C_{7}}$	0.0369	0.0108	0.0199	0.0249	0.0414	0.0116	0.0319	0.0181	0.0106	0.0107
$\mathbf{C_{8}}$	0.0230	0.0266	0.0222	0.0242	0.0083	0.0262	0.0196	0.0287	0.0040	0.0072
$\mathbf{C_{9}}$	0.0087	0.0307	0.0388	0.0116	0.0015	0.0220	0.0167	0.0353	0.0313	0.0128
$\mathbf{C_{10}}$	0.0140	0.0056	0.0375	0.0114	0.0124	0.0359	0.0107	0.0248	0.0150	0.0142
$\mathbf{C_{11}}$	0.0168	0.0377	0.0073	0.0260	0.0031	0.0291	0.0212	0.0191	0.0145	0.0287
$\mathbf{C_{12}}$	0.0102	0.0165	0.0398	0.0118	0.0327	0.0308	0.0400	0.0286	0.0036	0.0235
$\mathbf{C_{13}}$	0.0359	0.0368	0.0276	0.0139	0.0119	0.0294	0.0351	0.0037	0.0130	0.0237
$\mathbf{C_{14}}$	0.0317	0.0073	0.0074	0.0211	0.0119	0.0291	0.0210	0.0171	0.0298	0.0062
$\mathbf{C_{15}}$	0.0343	0.0050	0.0362	0.0142	0.0053	0.0122	0.0241	0.0279	0.0348	0.0375
$\mathbf{C_{16}}$	0.0307	0.0159	0.0379	0.0182	0.0257	0.0199	0.0039	0.0119	0.0032	0.0193
$\mathbf{C_{17}}$	0.0371	0.0099	0.0124	0.0253	0.0012	0.0132	0.0173	0.0310	0.0296	0.0214
$\mathbf{C_{18}}$	0.0072	0.0289	0.0020	0.0333	0.0038	0.0151	0.0372	0.0065	0.0170	0.0398
$\mathbf{C_{19}}$	0.0007	0.0296	0.0056	0.0267	0.0296	0.0049	0.0262	0.0304	0.0137	0.0039
$\mathbf{C_{20}}$	0.0050	0.0078	0.0103	0.0340	0.0051	0.0306	0.0190	0.0106	0.0253	0.0214
$\mathbf{C_{21}}$	0.0164	0.0051	0.0326	0.0106	0.0363	0.0121	0.0345	0.0164	0.0263	0.0275
$\mathbf{C_{22}}$	0.0206	0.0369	0.0337	0.0050	0.0421	0.0345	0.0233	0.0138	0.0256	0.0271
$\mathbf{C_{23}}$	0.0116	0.0140	0.0098	0.0313	0.0060	0.0251	0.0177	0.0206	0.0126	0.0362
$\mathbf{C_{24}}$	0.0134	0.0329	0.0152	0.0274	0.0214	0.0239	0.0023	0.0333	0.0222	0.0173
$\mathbf{C_{25}}$	0.0290	0.0172	0.0381	0.0065	0.0005	0.0265	0.0280	0.0097	0.0218	0.0014
$\mathbf{C_{26}}$	0.0353	0.0316	0.0005	0.0382	0.0310	0.0114	0.0156	0.0320	0.0003	0.0184
$\mathbf{C_{27}}$	0.0010	0.0150	0.0009	0.0063	0.0042	0.0167	0.0139	0.0077	0.0163	0.0180
$\mathbf{C_{28}}$	0.0163	0.0179	0.0038	0.0145	0.0235	0.0222	0.0318	0.0282	0.0059	0.0171
$\mathbf{C_{29}}$	0.0064	0.0297	0.0210	0.0311	0.0065	0.0098	0.0218	0.0302	0.0212	0.0133
$\mathbf{C_{30}}$	0.0140	0.0168	0.0014	0.0183	0.0372	0.0375	0.0168	0.0193	0.0262	0.0218
$\mathbf{C_{31}}$	0.0334	0.0005	0.0206	0.0173	0.0265	0.0085	0.0009	0.0247	0.0245	0.0373
$\mathbf{C_{32}}$	0.0184	0.0140	0.0249	0.0065	0.0199	0.0322	0.0032	0.0169	0.0060	0.0308
$\mathbf{C_{33}}$	0.0234	0.0148	0.0081	0.0333	0.0227	0.0203	0.0121	0.0079	0.0331	0.0184
$\mathbf{C_{34}}$	0.0143	0.0300	0.0015	0.0263	0.0395	0.0163	0.0189	0.0250	0.0360	0.0166
$\mathbf{C_{35}}$	0.0251	0.0055	0.0136	0.0392	0.0155	0.0098	0.0164	0.0193	0.0319	0.0151
$\mathbf{C_{36}}$	0.0091	0.0304	0.0386	0.0185	0.0209	0.0218	0.0128	0.0187	0.0338	0.0071
$\mathbf{C_{37}}$	0.0356	0.0247	0.0073	0.0190	0.0343	0.0222	0.0075	0.0233	0.0208	0.0229
$\mathbf{C_{38}}$	0.0175	0.0251	0.0237	0.0012	0.0394	0.0348	0.0315	0.0355	0.0174	0.0077
$\mathbf{C_{39}}$	0.0135	0.0357	0.0138	0.0268	0.0174	0.0081	0.0233	0.0191	0.0198	0.0199
$\mathbf{C_{40}}$	0.0057	0.0186	0.0019	0.0150	0.0362	0.0248	0.0248	0.0053	0.0239	0.0328
$\mathbf{C_{41}}$	0.0254	0.0249	0.0327	0.0045	0.0118	0.0378	0.0180	0.0354	0.0043	0.0270
$\mathbf{C_{42}}$	0.0370	0.0287	0.0093	0.0289	0.0048	0.0300	0.0389	0.0334	0.0350	0.0033
$\mathbf{C_{43}}$	0.0227	0.0162	0.0159	0.0111	0.0104	0.0022	0.0314	0.0338	0.0279	0.0198
$\mathbf{C_{44}}$	0.0357	0.0351	0.0267	0.0028	0.0223	0.0316	0.0262	0.0303	0.0020	0.0274
$\mathbf{C_{45}}$	0.0361	0.0160	0.0043	0.0211	0.0414	0.0139	0.0026	0.0268	0.0021	0.0349
$\mathbf{C_{46}}$	0.0131	0.0009	0.0415	0.0153	0.0312	0.0169	0.0070	0.0042	0.0328	0.0155
$\mathbf{C_{47}}$	0.0331	0.0375	0.0258	0.0324	0.0132	0.0010	0.0175	0.0169	0.0287	0.0327
$\mathbf{C_{48}}$	0.0029	0.0124	0.0413	0.0176	0.0048	0.0056	0.0248	0.0257	0.0332	0.0254
$\mathbf{C_{49}}$	0.0061	0.0268	0.0404	0.0184	0.0265	0.0166	0.0018	0.0118	0.0276	0.0107

technology is evident, especially when considering its environmental impacts and features that support advances in agriculture. Today, technological advances have accelerated rapidly. Companies also need to adapt to this situation. They should adopt efficient strategies that support technological developments in agriculture, considering environmental impacts. Another essential strategy is “Enhance Regulatory and Environmental Support (S3)” with a weight of 0.071. These strategies include supporting the developments needed for a sustainable supply chain. It is seen that these two strategies take into account environmental impacts. The least suitable strategy was evaluated as “Establish Buyer-Supplier Partnerships (S2),” with a low weight of -0.254. This strategy was assessed as low importance by 75% of the experts and medium importance by 25%, especially regarding the “High water consumption (C1)” criterion, which was selected as the second most important.

Overall, the study contributes significantly to determining a sustainable management strategy for the tea supply chain by providing a structured framework, expert-focused insights, and actionable recommendations. The findings provide perspectives for company managers to manage their supply chain processes efficiently in this perspective. In this context, the highlighted results reinforce the necessity for companies in the tea industry to prioritize ’Environmental’ focused strategy determination in their sustainable supply chain management.

6. Managerial and theoretical implications

The results of this study, with a focus on the tea industry in Türkiye, have significant theoretical implications, particularly in the area of supply chain sustainability in the agri-food sector. The findings highlight the importance of adopting digital technologies (S1), which emerged as the most effective strategy. This confirms existing sustainability theories that emphasize the role of technology and digital transformation in improving operational efficiency and reducing environmental footprints. In addition, factors such as high water consumption (C1) and carbon footprint (C12) contribute to the growing body of literature highlighting the environmental challenges in agricultural supply chains.

From a practical management perspective, the study provides actionable insights for supply chain managers and policymakers in the tea industry. For perspective, decision-makers can use the findings to prioritize adopting digital technologies (S1), which addresses the

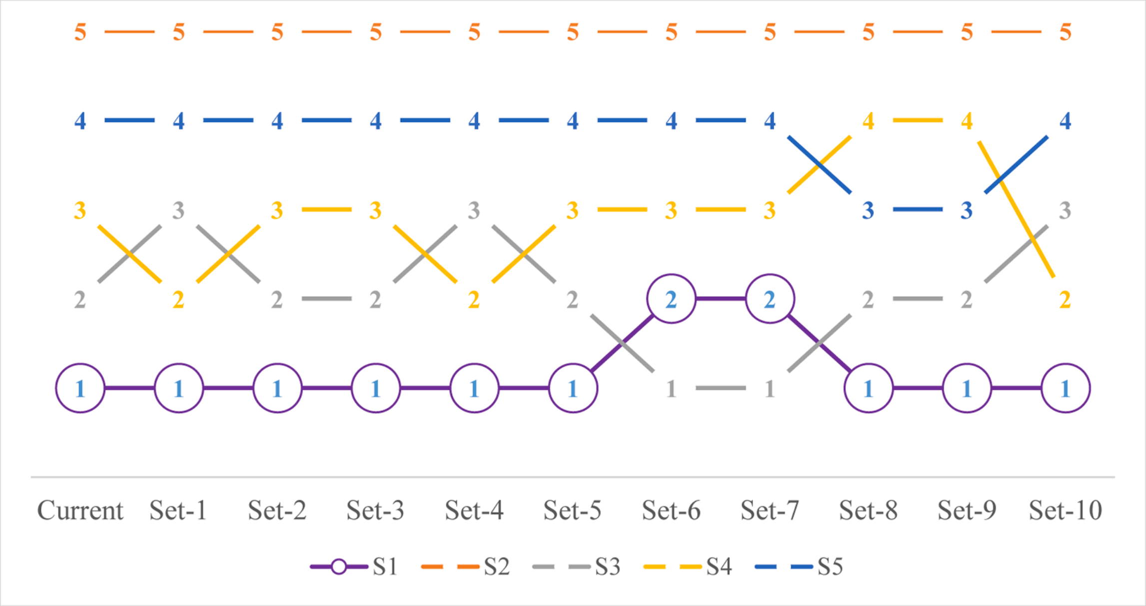

Fig. 5. Results of sensitivity analysis.

Table 16
Final scores of alternative strategies by SF-TOPSIS.

	S1	S2	S3	S4	S5
Final Score	0.1615	0.0063	0.0019	0.0151	0.0172
Ranking	1	4	5	3	2

Table 17
Final scores of alternative locations by SF-WISP.

	S1	S2	S3	S4	S5
Final Score	1.0000	0.9888	0.9987	0.9978	0.9946
Ranking	1	5	2	3	4

industry's immediate sustainability challenges and positions companies to remain competitive in a rapidly digitizing market.

These findings also underscore the need for managers to consider regulatory and environmental support (S3), which was ranked as a strong strategy, highlighting the importance of policy-driven sustainability initiatives. In addition, this study provides valuable guidance to industry stakeholders, including policymakers and sustainability advocates, by identifying key gaps in the tea supply chain's sustainability efforts. Social and economic factors, such as unemployment for local labor (C23) and insufficient investments (C28), highlight the broader impact of supply chain decisions on community welfare and economic stability. Policymakers can use these insights to develop targeted regulations and incentives addressing environmental and socio-economic concerns, ensuring a more holistic approach to the sustainability of the supply chain.

Overall, the study contributes significantly to determining a sustainable management strategy for the tea supply chain by providing a

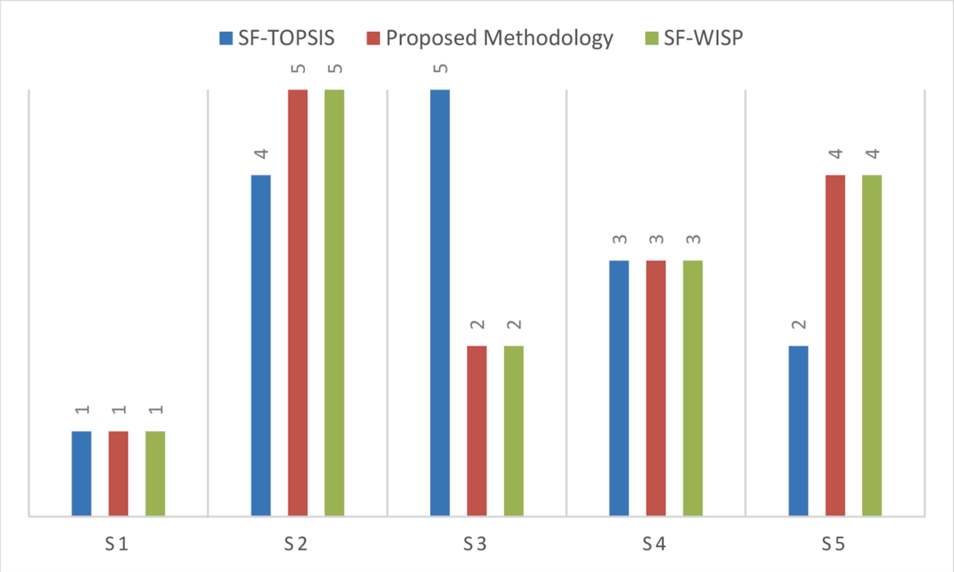

Fig. 6. The results of the comparative analysis.

structured framework, expert-focused insights, and actionable recommendations. The findings provide perspectives for company managers to manage their supply chain processes efficiently in this perspective. In this context, the highlighted results reinforce the necessity for companies in the tea industry to prioritize ’Environmental’ focused strategy determination in their sustainable supply chain management.

7. Conclusion

Sustainability has been the focus of many companies in recent years, especially in the supply chain area. Therefore, the scope of work in this context is also expanding. This study set out to address two primary research questions: (1) What are the most critical factors influencing the sustainability of the tea supply chain in Türkiye? (2) Which strategies are most effective in enhancing the sustainability of this supply chain? By applying a comprehensive MCDM approach, we sought to evaluate and prioritize a range of sustainability strategies based on an extensive set of criteria.

In this paper, we considered SSCM for the tea supply chain. We defined critical environmental, social, economic, and technical criteria within the sustainability framework and divided these main criteria into sub-criteria under various groups. For this purpose, we determined the criteria weights with SF-PIPRECIA, a novel MCDM method. As they differ from the literature, we integrated them into the SF-CODAS method by ranking the five alternative sustainable strategies. In addition, we conducted a sensitivity analysis to observe the sensitivity of the results to the criterion weights. This study contributes to essential issues such as sustainability, ASC, and SCM strategies in an integrated manner. This study focuses on the tea industry, an important income source for the Black Sea Region in Türkiye. It emphasizes issues that have not been previously addressed in the literature. It guides tea industry company managers in determining the most appropriate sustainable supply chain management strategy.

The study results revealed that "Adopt Digital Technologies" (S1) emerged as the most effective strategy for enhancing the sustainability of the tea supply chain in Türkiye, with a weight of 0.081, indicating its high relevance in addressing current challenges. "Enhance Regulatory and Environmental Support" (S3) was also identified as a strong alternative, highlighting the importance of governmental and environmental frameworks in driving sustainable practices. According to the results, the most and the least important main criteria are “environmental” and “financial,” respectively. However, the importance and value of all main criteria are close to each other. Sub-criteria related to the main environmental criterion are the most important. Furthermore, key sub-criteria such as carbon footprint (C_{12}) and high-water consumption (C_1) were the most critical factors impacting the sustainability of the supply chain, emphasizing the need for targeted interventions in these areas. The results illustrate that the proposed methodology effectively selects a management strategy for the tea supply chain. Additionally, this study proposes the advantage of the practical use of MCDM methods for policymakers and companies.

In addition, to underscore the novelty of sustainability in this research, we have integrated spherical fuzzy MCDM techniques, which allow for the nuanced handling of uncertainties across environmental, social, economic, and technical areas. By systematically weighting and prioritizing criteria relevant to long-term resilience, our model highlights how targeted investments can promote both profitability and environmental stewardship in the tea supply chain. This approach goes beyond traditional sustainability frameworks and provides a holistic method for identifying interventions that can simultaneously strengthen environmental protection, social well-being and operational efficiency, clearly aligning our findings with the study’s objectives.

This study makes several significant contributions to both theory and practice. Theoretically, it extends the application of MCDM methodologies by integrating a comprehensive set of sustainability criteria tailored explicitly for the agri-food sector. This provides a novel framework for future studies evaluating supply chain sustainability in other contexts. Practically, the results offer valuable insights for industry stakeholders, policymakers, and supply chain managers within the tea industry and beyond, highlighting actionable strategies that can lead to improved sustainability outcomes. The study also addresses critical sustainability gaps in the tea supply chain, providing a structured approach to prioritizing interventions supporting long-term resilience and efficiency. Incorporating MCDM methodologies confirms that the decision-making process is comprehensive and adaptable to changing related conditions and priorities. Additionally, the proposed methodology reduces the complexity of the problem, facilitating more sustainable decisions.

There are some limitations to this research on sustainable tea supply chains. Firstly, Turkiye was selected as the study area. Geographical bias may have an impact on the results and may also limit the generalizability of the findings. The expert team brings different viewpoints. Nevertheless, there is subjectivity due to the determination of an expert team and probable biases in their research field. An additional limitation of this research is access to different expert levels. The use of SF-PIPRECIA and SF-CODAS methods in this study is novel but may have essential limitations that still need to be addressed. Moreover, even though the literature review is comprehensive, it might overlook new challenges that still need to be recognized in the literature. The absence of any similar study in the sustainable tea supply chain study, to the best of our knowledge, the literature prevents the results from being compared with other methods. The literature review is limited to studies published up to the latest date for the time of this study, which may result in missing recent developments. Furthermore, external factors such as regulatory changes might affect the importance of the identified challenges.

Several aspects of this paper can be addressed in future work, such as different strategies defined for different ASCMs. Future research directions for this study could focus on expanding the scope of the sustainability criteria and strategies considered, particularly by incorporating additional case studies from different regions or sectors within the agri-food industry. Exploring how emerging technologies such as blockchain, artificial intelligence, and precision agriculture can further enhance sustainability in supply chains could provide new insights. Second, conducting longitudinal studies to assess the long-term impact of the prioritized strategies on supply chain sustainability would be valuable. Third, incorporating stakeholder perspectives, such as farmers, consumers, and policymakers, could enrich the analysis by providing a more holistic understanding of the challenges and opportunities in achieving sustainability. Fourth, integrating dynamic and real-time data in the decision-making process could lead to more adaptive and resilient supply chain strategies in the future. Fifth, the proposed approach offers potential avenues for extending the model to encompass other groups of fuzzy sets, such as complex spherical fuzzy sets [120–122], T-spherical fuzzy Sets [123,124] and complex T-spherical fuzzy sets [125–127]. Sixth, different fuzzy-based MCDM methods can be applied to weigh the criteria and used to rank the alternatives. Finally, the proposed methodology can be used for other SSCM problems.

CRediT authorship contribution statement

Betul Yildirim: Writing – original draft, Resources, Methodology, Data curation, Conceptualization. **Ertugrul Ayyildiz:** Writing – original draft, Software, Resources, Methodology, Data curation, Conceptualization. **Nezir Aydin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.100710.

Data availability

Data will be made available on request.

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