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Strategic Procurement Prioritization for Sustainable Aviation Fuel: An Integrated Pythagorean Fuzzy SWARA–RAM Decision Support Framework

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ABSTRACT

The transition toward sustainable aviation fuel (SAF) has become a strategic priority for commercial airlines seeking to reduce aviation-related emissions while maintaining secure and economically viable fuel procurement. However, procurement decisions remain challenging because airlines must simultaneously balance environmental objectives, supply security, economic feasibility, operational considerations, and evolving policy requirements under substantial uncertainty. Existing studies primarily focus on technological production pathways or policy issues, whereas systematic evaluations of alternative SAF procurement strategies from an airline procurement perspective remain limited. This study develops an integrated multi-criteria decision support framework to prioritize sustainable aviation fuel procurement strategies for commercial airlines under uncertainty. The proposed framework combines Pythagorean fuzzy sets, Stepwise Weight Assessment Ratio Analysis (SWARA), and the Reliability, Availability and Maintainability (RAM) method to represent uncertainty in expert judgments, determine the relative importance of evaluation criteria, and prioritize procurement alternatives. The findings indicate that lifecycle carbon reduction potential and local emission reduction are the highest-priority evaluation criteria, while partnership or investment in SAF production facilities represents the highest-ranked procurement strategy according to the participating experts, with comparative analysis using the COPRAS method confirming the consistency of the ranking results. The proposed framework provides structured decision support for strategic procurement planning by integrating environmental, economic, operational, and geopolitical considerations, offering expert-informed guidance for airline procurement managers and a foundation for future studies incorporating operational and market-based evidence.

1. Introduction

Aviation is responsible for a substantial share of global greenhouse gas emissions, and its contribution is expected to increase as passenger demand continues to grow over the coming

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decades. Unlike many other transport sectors, aviation has limited short-term decarbonization options because large-scale electrification and hydrogen-powered commercial aircraft remain technologically and economically constrained. Consequently, sustainable aviation fuel (SAF) has emerged as the most practical near and medium-term solution for reducing lifecycle carbon emissions from air transport. Despite its strategic importance, global SAF deployment remains extremely limited. Recent industry estimates indicate that SAF accounted for less than one percent of total jet fuel consumption worldwide in 2025, highlighting a substantial gap between current production capacity and international decarbonization ambitions. At the same time, ICAO identifies SAF as the technology with the greatest potential to reduce carbon emissions from international aviation and supports its widespread deployment as a key component of the sector's long-term net-zero strategy. These figures clearly demonstrate that improving the efficiency and resilience of SAF supply chains is no longer merely an operational issue but a strategic necessity for accelerating aviation decarbonization [1].

To optimize the sustainable aviation fuel supply chain, airlines need to adopt several strategic procurement strategies that address both availability and long-term cost stability. One important action is establishing long term supply agreements with domestic SAF producers, which can reduce dependence on external markets and improve supply reliability. Such agreements also support the development of local production capacity and strengthen national energy security. At the same time, airlines may prefer a diversified international sourcing strategy that involves multiple suppliers from different regions. This approach reduces the risk of disruption caused by regional shocks or policy changes. Another strategic option is direct investment in SAF production facilities through joint ventures or equity participation. Vertical integration allows firms to gain greater control over production processes, pricing, and quality standards. In addition, many firms are increasingly focusing on waste based SAF technologies that use agricultural residues, used cooking oil, or municipal waste [2]. These technologies can reduce feedstock competition with food resources and improve the environmental credibility of SAF. Together, these actions contribute to a more resilient and efficient supply chain that supports both operational continuity and sustainability objectives. Sustainable aviation fuel procurement should be viewed as a hybrid decision domain that combines both strategic and tactical dimensions. Strategic procurement decisions involve long-term commitments such as investment in production facilities, long-term supply agreements, and the development of resilient sourcing portfolios, whereas tactical procurement focuses on supplier selection, procurement timing, and operational purchasing decisions. Since airlines must simultaneously achieve environmental objectives, supply security, regulatory compliance, and economic efficiency, SAF procurement requires a comprehensive decision support framework capable of integrating these multiple dimensions.

When selecting among these strategies, companies must evaluate a range of criteria that reflect financial, environmental, and strategic considerations. Economic and cost related criteria are often the first concern, as SAF remains more expensive than conventional jet fuel. Firms need to assess investment costs, long term fuel prices, and potential cost savings from stable supply arrangements. Environmental and technical emission criteria are also critical, since the primary motivation for SAF adoption is emission reduction. Different SAF pathways offer varying levels of lifecycle emission savings, and these differences should be carefully evaluated. Technical compatibility with existing aircraft and infrastructure is another important aspect. In addition, geopolitical and strategic risk criteria play a significant role in decision making. Dependence on specific regions or suppliers may expose firms to political instability, trade restrictions, or regulatory uncertainty [3]. By considering these criteria together, firms can make more balanced and informed decisions that align sustainability goals with economic and operational realities.

For effective strategic prioritization, it is necessary to identify and prioritize the most suitable strategies within the sustainable aviation fuel supply chain. This prioritization process is critical because it allows firms to implement the right actions in a timely and coordinated manner. Without clear priorities, companies may invest in inefficient solutions and face excessively high costs. Such cost pressures can negatively affect financial performance and limit the ability of firms to scale up SAF usage. Although this issue is highly relevant, the existing literature provides limited guidance on how to systematically identify the most important criteria and strategies. Most studies focus on technological aspects or policy discussions, while integrated decision frameworks remain rare [4]. This lack of structured analysis creates a significant research gap. As a result, firms often rely on fragmented information or subjective judgment when making strategic decisions. This situation reduces decision quality and increases uncertainty. Addressing this gap is therefore important not only for academic advancement but also for practical decision making in the aviation industry.

This study adopts the perspective of commercial airlines as the primary decision makers and aims to prioritize strategic sustainable aviation fuel procurement alternatives rather than optimize physical supply chain operations. The proposed framework is intended to support airline managers in selecting the most appropriate procurement strategy under economic, environmental, and strategic uncertainty. The main motivation of the study arises from the increasing cost pressures, supply risks, and strategic uncertainty faced by aviation firms during the transition to sustainable fuels, as well as the limited guidance offered by existing literature on how to prioritize SAF related strategies in a systematic way. To address this challenge, the study employs an integrated multi-criteria decision-making framework. SWARA is used to derive the relative importance of the evaluation criteria from expert judgments through a structured weighting procedure. The RAM method subsequently ranks procurement strategies by simultaneously considering benefit and cost attributes. To better represent the uncertainty and hesitation inherent in expert evaluations, Pythagorean fuzzy sets are incorporated throughout the decision-making process.

Within this framework, the study seeks to answer the following research questions:

RQ1: Which procurement evaluation criteria are the most influential for strategic sustainable aviation fuel procurement decisions from the perspective of commercial airlines?

RQ2: How should alternative sustainable aviation fuel procurement strategies be prioritized under economic, environmental, operational, and geopolitical uncertainty?

RQ3: Which procurement strategy provides the best overall performance by simultaneously balancing economic feasibility, environmental sustainability, supply chain resilience, and regulatory compatibility?

This study makes both practical and methodological contributions to the sustainable aviation fuel literature. From a practical perspective, it provides airline decision makers with a structured framework for prioritizing sustainable aviation fuel procurement strategies by simultaneously considering economic, environmental, operational, and geopolitical factors. The proposed framework supports more transparent procurement decisions and may assist airlines in improving supply security while advancing their sustainability objectives. From a methodological perspective, the study integrates SWARA, RAM, and Pythagorean fuzzy sets into a unified multi-criteria decision-making framework. SWARA is employed to determine the relative importance of evaluation criteria, RAM is used to prioritize procurement strategies by considering both benefit and cost attributes, and Pythagorean fuzzy sets enable expert judgments to be represented under uncertainty. This integrated approach offers a practical and transparent decision support tool that can also be adapted to other strategic procurement problems within the aviation sector. Rather than proposing a mathematical optimization model for physical supply chain operations, this study focuses on supporting strategic procurement decision making by systematically prioritizing alternative SAF procurement strategies under multiple and conflicting evaluation criteria. Accordingly, the contribution of the proposed framework lies in improving the quality and transparency of procurement decisions rather than optimizing logistical operations. This distinction clarifies the managerial scope of the proposed decision support model and aligns its objectives with the practical challenges faced by commercial airlines during the transition toward sustainable aviation fuels. The methodological contribution of this study does not stem from proposing a new multi-criteria decision-making algorithm. Instead, it lies in the development of an integrated decision-support framework that combines established methods within a procurement-oriented decision structure specifically designed for sustainable aviation fuel strategy prioritization. The novelty therefore resides in the problem formulation, the integration of complementary analytical techniques, and their application to an underexplored procurement decision context rather than in the introduction of a completely new computational method.

The remainder of this study is structured as follows. The second section presents a comprehensive review of the relevant literature, focusing on sustainable aviation fuel, supply chain management, and multi criteria decision making approaches. The third section introduces the proposed methodology in detail and explains the integrated decision-making model, including the criteria, alternatives, and analytical techniques employed. In the fourth section, the analysis results are reported, and the prioritized strategies are presented based on the empirical findings. The fifth section discusses these results by comparing them with existing studies and highlighting their theoretical and practical implications. Finally, the sixth section concludes the study by summarizing the main findings, outlining limitations, and suggesting directions for future research.

2. Literature Review

Existing studies on sustainable aviation fuel primarily focus on four interrelated research streams: economic feasibility and production costs, environmental performance, supply chain resilience, and policy or regulatory challenges. Although these studies have substantially improved the understanding of SAF adoption, they generally examine these dimensions separately. This review critically evaluates the existing literature across these themes and identifies the remaining research gap that motivates the development of the proposed decision support framework.

Economic feasibility has been recognized as one of the primary barriers to large-scale sustainable aviation fuel adoption. Xu *et al.* [5] emphasize that the high cost of SAF production is a major obstacle to widespread adoption and that cost reduction depends on economies of scale and government support. Braun *et al.* [6] show that current SAF costs are high compared to conventional fuel, but that the difference may decrease in the medium term with policy incentives and technological maturity. Cui and Chen [7] state that SAF use provides economic burden in the short term and societal benefits through carbon reduction in the long term. Liang *et al.* [8] show that logistics and distribution costs limit the economic viability of SAF and that network optimization and reduction of transportation distances reduce costs. Akter *et al.* [9] reveal that in SAF production based on forest residues, the supply chain affects the cost depending on the facility location and raw material intensity, and that decentralized production is advantageous. Oetzel *et al.* [10] demonstrate that on-site SAF blending at airports can reduce costs, fuel prices, and carbon emissions, highlighting the strategic importance of infrastructure restructuring. Yang and Yao [11] show that uncertainties in feedstock and process data in SAF production pathways affect cost performance and long-term price volatility. Carlson *et al.* [12] reveal that Monte Carlo simulation is critical for evaluating cost fluctuations and economic risks in the integration of bio-blendstocks into refineries.

Beyond economic considerations, environmental performance constitutes another major research stream within the sustainable aviation fuel literature. Lan *et al.* [13] demonstrate that SAF produced from paper pulp can significantly reduce CO_2 emissions throughout its life cycle compared to conventional fuels with proper recycling. Quiroz *et al.* [14] show that biomass-based SAF pathways such as miscanthus can achieve low CO_2e levels in line with the 2050 targets and contribute to the net-zero goal. Zhang *et al.* [15] compare the carbon emissions of SAF pathways such as HEFA, FT, ATJ, and PtL, showing that PtL has a high carbon reduction potential. Liu and Yang [16] show that FT SAF blends improve thrust, fuel consumption, and emission performance, but that careful testing is necessary for optimum blend. Emmanouilidou *et al.* [17] show that feedstocks with low environmental risk, such as waste biomass, offer sustainable alternatives in SAF production, but the lack of technological maturity and scalability limits the benefits. Yoo *et al.* [18] reveal that with appropriate production processes, lignocellulosic biomass and algae feedstocks can provide a 55–92% GHG emission reduction compared to fossil jet fuel. Xu *et al.* [19] demonstrate that 100% HEFA-based SAF reduces PM emissions by 70–90% in small turbofan engines, positively impacting local air quality.

From a theoretical perspective, the present study is grounded in strategic procurement and strategic sourcing principles within supply chain management. These perspectives emphasize that procurement decisions extend beyond transactional purchasing activities and constitute long-term strategic choices that influence organizational resilience, cost efficiency, environmental performance, and supply security. Sustainable aviation fuel procurement exemplifies such a strategic decision problem because airlines must simultaneously balance multiple conflicting objectives under considerable uncertainty. Consequently, the proposed decision-support framework is designed to support strategic procurement prioritization by integrating economic, environmental, operational, and geopolitical considerations within a unified analytical structure.

Previous SAF studies provide important but largely fragmented insights into the decision problem addressed in this research. For example, Liang *et al.* [8] examine SAF supply-chain challenges and modeling advances and Xu *et al.* [5] review SAF research from an economic and management perspective. Other studies primarily concentrate on specific dimensions, including production costs and economic feasibility [2, 6], environmental performance and lifecycle emissions [13, 14], and regulatory and scalability challenges. Although these studies provide valuable evidence for SAF development and deployment, they do not provide an integrated expert-based framework specifically designed to prioritize competing SAF procurement strategies from the perspective of commercial airlines. Moreover, the existing literature gives limited attention to simultaneously incorporating economic, environmental, operational, geopolitical, and regulatory considerations into such procurement decisions under uncertainty. The present study addresses this gap by integrating Pythagorean fuzzy sets with SWARA and RAM in a procurement-oriented decision structure. Its novelty therefore does not arise from proposing a new MCDM algorithm, but from formulating SAF procurement as a multi-dimensional strategic prioritization problem and combining uncertainty representation, criteria weighting, and alternative ranking within a unified framework tailored to commercial airline decision making.

Furthermore, only a limited number of studies employ multi-criteria decision-making techniques to address procurement decisions under uncertainty. To address these shortcomings, the present study develops an integrated SWARA–RAM framework supported by Pythagorean fuzzy sets to prioritize sustainable aviation fuel procurement strategies for airline decision makers. The proposed framework is not intended to replace alternative decision-making techniques. Instead, it is specifically designed for procurement problems characterized by multiple conflicting criteria, limited quantitative information, and uncertainty in expert judgments. Under these conditions, integrating Pythagorean fuzzy sets with SWARA and RAM provides a transparent and systematic mechanism for representing uncertainty, determining criteria importance, and prioritizing procurement strategies.

Therefore, the contribution of the framework lies in its suitability for the characteristics of the decision problem rather than in claiming universal methodological superiority.

3. Methodology

This section includes the definitions of Pythagorean fuzzy sets (PFSs), SWARA and RAM, respectively. PFSs are used to perform operations using linguistic expressions from experts. The SWARA method is preferred for obtaining priority values of criteria, while the RAM method is used for ranking strategic procurement approaches. Figure 1 illustrates the overall workflow of the proposed framework. Following the determination of criteria weights using SWARA and the prioritization of procurement strategies through the RAM method, an independent validation branch is conducted using the COPRAS method. The comparative analysis between RAM and COPRAS provides an additional robustness assessment by examining the consistency of the resulting rankings through correlation analysis. This validation procedure strengthens the reliability of the proposed decision-making framework.

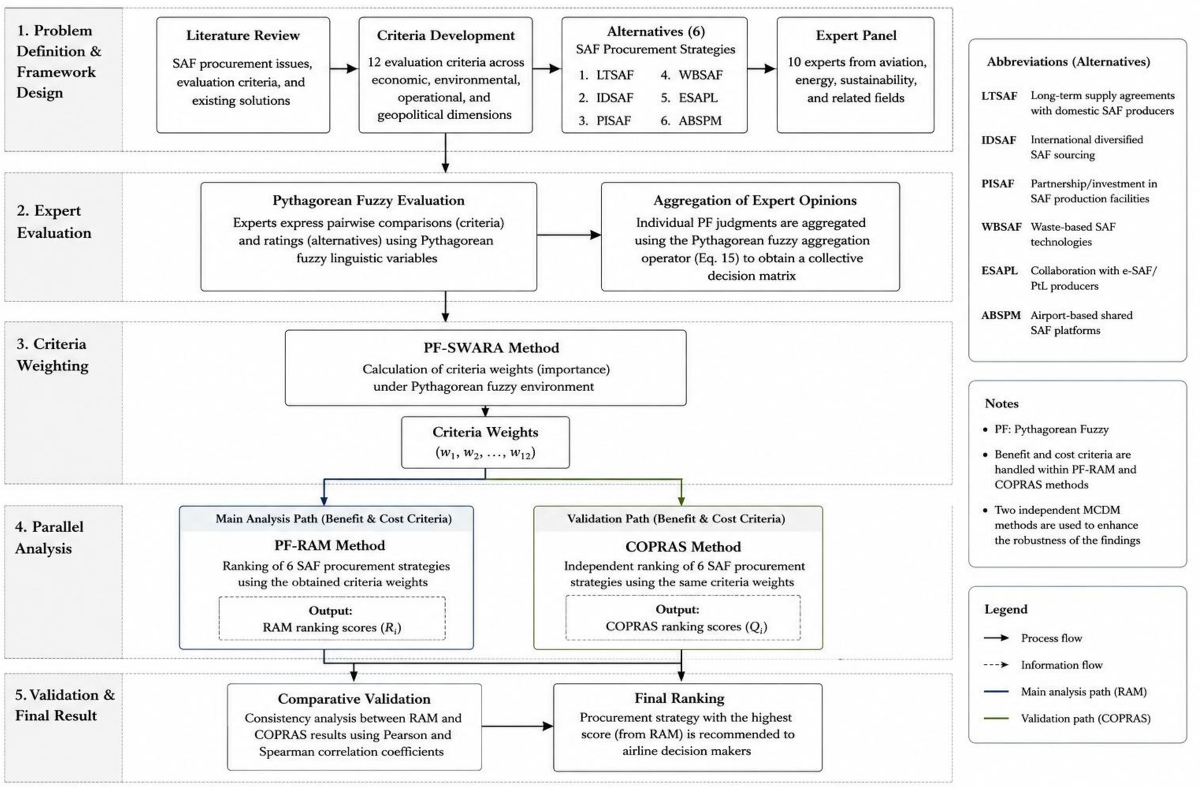

Fig. 1. Flowchart of proposed decision-making process

Figure 1 illustrates the complete workflow of the proposed decision-making framework. The process follows a sequential rather than iterative structure. First, the evaluation criteria and procurement alternatives are identified through literature review and expert consultation. Expert judgments are subsequently expressed using Pythagorean fuzzy linguistic variables, where PF refers to Pythagorean fuzzy representations. The criteria are weighted using the SWARA method, after which the RAM approach is applied to rank the procurement alternatives. The final decision rule is based on the ranking scores generated by the RAM method, with the procurement strategy obtaining the highest-ranking score considered the most appropriate alternative. Since the expert panel reached consensus regarding the evaluation framework before the analysis stage, no additional iterations were required during the computational process.

The proposed framework integrates Pythagorean fuzzy sets, SWARA, and RAM because each method addresses a different stage of the procurement decision process. Pythagorean fuzzy sets are employed to represent uncertainty and hesitation in expert judgments more effectively than crisp evaluations. Building upon these uncertainty-aware assessments, the SWARA method determines the relative importance of the evaluation criteria through a transparent expert-driven weighting procedure [20]. The resulting weights are subsequently incorporated into the RAM method, which evaluates and prioritizes alternative procurement strategies by simultaneously considering benefit and cost criteria. Accordingly, the three methods perform complementary rather than overlapping functions [21]. Their sequential integration enables uncertainty representation, criteria weighting, and alternative prioritization within a unified decision-support framework, thereby providing more comprehensive managerial insights than the application of any individual method alone [22].

3.1. Notation and Computational Structure

For clarity and reproducibility, let (A={A1, A2, …, Am}) denote the set of procurement alternatives, (C={C1, C2, …, Cn}) denote the set of evaluation criteria, and (E={E1, E2, …, Ek}) denote the set of experts. Accordingly, (i=1,…,m) is the alternative index, (j=1,...,n) is the criterion index, and (t=1…,k) is the expert index. In the present application, (m=6), (n=12), and (k=10). A Pythagorean fuzzy number is represented as (P=(μ,ν)), where μ∈[0, 1] denotes the membership degree and ν∈[0, 1] denotes the non-membership degree, subject to the condition 0≤μ2+ν2≤1. The associated degree of indeterminacy is calculated as π=1−μ2−ν2. Thus, the Pythagorean fuzzy representation explicitly accommodates the hesitation remaining after membership and non-membership have been specified.

The computational procedure follows a sequential input–transformation–output structure. First, the linguistic evaluations provided by the experts constitute the initial input and are converted into Pythagorean fuzzy numbers using the linguistic scale reported in Table 1, producing the initial PF decision matrices. For criterion weighting, individual expert evaluations are aggregated to obtain collective PF evaluations, which are subsequently converted into crisp values and processed through the SWARA steps to generate the final criterion weights. These weights constitute the output of PF-SWARA and simultaneously serve as an input to PF-RAM. For alternative ranking, the expert evaluations of each procurement alternative with respect to each criterion are converted and aggregated into PF decision values. The criterion weights obtained from PF-SWARA are then incorporated into these evaluations to construct the weighted decision matrix. The weighted values are subsequently processed according to the benefit and cost classification of the criteria, and the resulting components are combined through the RAM procedure to calculate the final ranking score for each alternative. Therefore, each computational stage generates an output that serves as the input to the subsequent stage, allowing the complete procedure to be traced from the original linguistic expert judgments to the final procurement-strategy ranking.

3.2. Pythagorean Fuzzy Sets

Fuzzy sets define the grade of membership of an object in the discourse universe to a particular set. One type of fuzzy set, PFSs, performs this definition using the grades of belonging, non-belonging, and indeterminacy of an object [23]. A PFS $(\tilde{P})$ on universe of discourse (D) is described as Eq. (1).

$$\tilde{P} = \left\{\langle s, \left(\alpha_{\tilde{P}}(s), \beta_{\tilde{P}}(s)\right)\rangle | s \in D\right\} \tag{1}$$

Where these grades are between zero and one with condition in Eq. (2).

$$0 \leq \left(\alpha_{\tilde{P}}(s)\right)^2 + \left(\beta_{\tilde{P}}(s)\right)^2 \leq 1 \tag{2}$$

For each $s \in D$, the indeterminacy grade is identified by Eq. (3).

$$\gamma_{\tilde{P}}(s) = \sqrt{1 - \alpha_{\tilde{P}}^2(s) - \beta_{\tilde{P}}^2(s)} \quad (3)$$

Pythagorean fuzzy number (PFN) is shown with $\tilde{P} = (\alpha_{\tilde{P}}, \beta_{\tilde{P}})$ and $0 \leq \alpha_{\tilde{P}}^2 + \beta_{\tilde{P}}^2 \leq 1$. For this number, score and accuracy values are defined using Eqs. (4) and (5), respectively.

$$\mathbb{S}(\tilde{P}) = (\alpha_{\tilde{P}})^2 - (\beta_{\tilde{P}})^2 \quad (4)$$

$$\hbar(\tilde{P}) = (\alpha_{\tilde{P}})^2 - (\beta_{\tilde{P}})^2 \quad (5)$$

The normalized score and uncertainty functions are computed via Eqs. (6) and (7), respectively.

$$\mathbb{S}'(\tilde{P}) = 0.5(\mathbb{S}(\tilde{P}) + 1) \quad (6)$$

$$\hbar'(\tilde{P}) = 1 - \hbar(\tilde{P}) \quad (7)$$

Where $\mathbb{S}'(\tilde{P}), \hbar'(\tilde{P}) \in [0, 1]$. Assume that $\tilde{P} = (\alpha_{\tilde{P}}, \beta_{\tilde{P}}), \tilde{P}_1 = (\alpha_{\tilde{P}_1}, \beta_{\tilde{P}_1})$ and $\tilde{P}_2 = (\alpha_{\tilde{P}_2}, \beta_{\tilde{P}_2})$ are three PFNs. Then, some processes on PFNs are summarized in Eqs. (8) – (12).

$$\tilde{P}^c = (\beta_{\tilde{P}}, \alpha_{\tilde{P}}) \quad (8)$$

$$\tilde{P}_1 \oplus \tilde{P}_2 = \left(\left(\alpha_{\tilde{P}_1}^2 + \alpha_{\tilde{P}_2}^2 - \alpha_{\tilde{P}_1}^2\alpha_{\tilde{P}_2}^2\right)^{0.5}, \beta_{\tilde{P}_1}\beta_{\tilde{P}_2}\right) \quad (9)$$

$$\tilde{P}_1 \otimes \tilde{P}_2 = \left(\alpha_{\tilde{P}_1}\alpha_{\tilde{P}_2}, \left(\beta_{\tilde{P}_1}^2 + \beta_{\tilde{P}_2}^2 - \beta_{\tilde{P}_1}^2\beta_{\tilde{P}_2}^2\right)^{0.5}\right) \quad (10)$$

$$\rho\tilde{P} = \left(\left(1 - \left(1 - \alpha_{\tilde{P}}^2\right)^{\rho}\right)^{0.5}, (\beta_{\tilde{P}})^{\rho}\right);\ \rho > 0 \quad (11)$$

$$\tilde{P}^{\rho} = \left((\alpha_{\tilde{P}})^{\rho}, \left(1 - \left(1 - \beta_{\tilde{P}}^2\right)^{\rho}\right)^{0.5}\right);\ \rho > 0 \quad (12)$$

Distance between $\tilde{P}_1$ and $\tilde{P}_2$ is estimated by Eq. (13).

$$\Delta(\tilde{P}_1, \tilde{P}_2) = 0.5\left(\left|\alpha_{\tilde{P}_1}^2 - \alpha_{\tilde{P}_2}^2\right| + \left|\beta_{\tilde{P}_1}^2 - \beta_{\tilde{P}_2}^2\right| + \left|\gamma_{\tilde{P}_1}^2 - \gamma_{\tilde{P}_2}^2\right|\right) \quad (13)$$

For clarity and consistency, the main mathematical notation used throughout the proposed framework is defined as follows. Let (i=1,…,m) denote the procurement alternatives, (j=1…,n) denote the evaluation criteria, and (t=1…,k) denote the participating experts. A Pythagorean fuzzy number is represented by a membership degree and a non-membership degree, while the associated hesitation degree reflects the remaining uncertainty in the evaluation. In the PF-SWARA procedure, the aggregated Pythagorean fuzzy evaluations are first converted into crisp values and arranged in descending order. The relative importance, coefficient, recalculated importance, and normalized weight of each criterion are then obtained sequentially according to the corresponding equations. In the PF-RAM procedure, the Pythagorean fuzzy evaluation of alternative (i) with respect to criterion (j), provided by expert (t), is first aggregated and subsequently combined with the criterion weight obtained from PF-SWARA. The weighted evaluations are then separated according to benefit and cost criteria and combined through the RAM calculation procedure to obtain the final ranking score for each procurement alternative. The alternative with the highest final ranking score is considered the most preferred procurement strategy.

3.3. PF-SWARA

SWARA is a subjective weighting method that presents the importance weights of the criteria using a stepwise approach. The calculation of PFNs using this method is as follows [24].

Firstly, n criteria are identified. Next, opinions about criteria of k experts are collected using linguistic variables in Table 1.

The linguistic scale presented in Table 1 was employed to provide experts with a sufficiently detailed but structured set of qualitative assessment levels ranging from “Absolutely Low” to “Absolutely High.” The use of multiple ordered linguistic terms enables experts to distinguish between different levels of perceived importance or performance without requiring them to provide precise numerical judgments. Each linguistic term is represented by a Pythagorean fuzzy number consisting of membership and non-membership degrees.

Table 1
Linguistic Variables

Term	PFN
Absolutely high(AH)	(0.95,0.2)
Very very high(VVH)	(0.85,0.3)
Very high (VH)	(0.8,0.35)
High(H)	(0.7,0.45)
Medium high(MH)	(0.6,0.55)
Medium (M)	(0.5,0.6)
Medium low(ML)	(0.4,0.7)
Low(L)	(0.3,0.75)
Very low(VL)	(0.2,0.85)
Absolutely low(AL)	(0.1,0.95)

In this representation, the membership degree reflects the extent to which an evaluation supports the corresponding linguistic assessment, whereas the non-membership degree reflects the extent to which it does not support that assessment. The numerical pairs were defined as a predefined and internally consistent Pythagorean fuzzy linguistic scale, with progressively higher linguistic assessments generally associated with higher membership and lower non-membership degrees. The selected values also satisfy the Pythagorean fuzzy condition and preserve a degree of hesitation, allowing uncertainty in expert judgments to be represented rather than forcing assessments into exact crisp values. Accordingly, the purpose of the scale is not to claim that these numerical pairs constitute empirically calibrated measurements, but to provide a consistent mathematical representation of qualitative expert judgments. All experts used the same linguistic scale, thereby ensuring a common semantic and computational basis for the subsequent aggregation and decision-making procedures. Thus, PF-initial decision matrix is obtained as Eq. (14).

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{k1} & \cdots & \tilde{x}_{kn} \end{bmatrix} \tag{14}$$

Where $\tilde{x}_{ij} = \left(\alpha_{\tilde{x}_{ij}}, \beta_{\tilde{x}_{ij}}\right)$. Since the study involves evaluations from ten experts, individual judgments must be aggregated into a collective assessment before calculating the criteria weights. Equal expert weighting was adopted because all participants satisfied the same predefined eligibility requirements, including substantial relevant professional experience and expertise in aviation, energy, sustainability, or strategic procurement. Moreover, the panel was intentionally composed of experienced professionals with comparable levels of domain knowledge, and no objective evidence was available to justify assigning greater decision-making authority to any participant. Equal weighting therefore avoids introducing an additional subjective layer into the aggregation process and ensures that each qualified expert contributes equally to the collective assessment. Nevertheless, alternative weighting schemes based on factors such as professional experience, domain specialization, or institutional background could modify the aggregated evaluations and potentially influence the resulting criteria weights and alternative rankings. Examining the sensitivity of the results to different expert-weighting assumptions therefore represents a valuable direction for future research. Next, PF-aggregated values are calculated using Eq. (15).

$$\widetilde{agg}_j = \left(\left(1 - \prod_{i=1}^{k}\left(1 - \alpha_{\tilde{x}_{ij}}^2\right)^{\frac{1}{k}}\right)^{0.5}, \prod_{i=1}^{k}\left(\beta_{\tilde{x}_{ij}}\right)^{\frac{1}{k}}\right) \tag{15}$$

Afterwards, the crisped values are computed with Eq. (16).

$$agg_j = \mathbb{S}'\left(\widetilde{agg}_j\right) \tag{16}$$

The criteria are sorted in descending order according to their crisped values. Next, relative values are estimated by calculating the difference between the crisped values and the previous values. Then, coefficients of criteria are established by Eq. (17).

$$c_j = \begin{cases} 1; j = 1 \\ r_j + 1; j > 1 \end{cases} \tag{17}$$

Where r refers to the relative value. Recalculated values are obtained with the help of Eq. (18).

$$rc_j = \begin{cases} 1; j = 1 \\ rc_{j-1}/c_j; j > 1 \end{cases} \tag{18}$$

Finally, the weights of criteria are defined as Eq. (19).

$$w_j = \frac{rc_j}{\sum_{j=1}^{n} rc_j} \tag{19}$$

The PF-SWARA procedure transforms the initial expert evaluations into normalized criterion weights through a sequential calculation process. First, each expert evaluates the importance of each criterion using the linguistic scale presented in Table 1, and these linguistic assessments are converted into their corresponding Pythagorean fuzzy numbers. The individual PF evaluations are then aggregated across the (k) experts to obtain a collective PF evaluation for each criterion. Each aggregated PF value is subsequently transformed into a crisp value using the defuzzification function defined in Eq. (16). The criteria are then arranged in descending order according to these crisp values. For each criterion (j), starting from the second-ranked criterion, the comparative importance value (sj) is calculated as the difference between the crisp value of the immediately preceding criterion and that of criterion (j). The coefficient (kj) is then calculated from (sj), after which the recalculated importance value (qj) is obtained recursively, with the highest-ranked criterion assigned an initial value of (q1=1). Finally, the normalized weight of each criterion is calculated as ($w_j = \frac{q_j}{\sum_{j=1}^{n} q_j}$), ensuring that $\sum_{j=1}^{n} w_j = 1$. All calculations were performed using the unrounded numerical values generated at each computational stage. Values reported in the tables were rounded to three decimal places for presentation purposes only. Consequently, the displayed weights in Table 6 sum to 0.999 because of rounding, whereas the unrounded criterion weights used in the subsequent PF-RAM calculations are normalized to exactly 1.

3.4. PF- Root Assessment Method

The Root Assessment Method (RAM) is an MCDM technique originally introduced by Sotoudeh-Anvari [25] for evaluating and ranking a finite set of alternatives with respect to multiple benefit and cost criteria. In the present study, the acronym RAM therefore refers exclusively to the Root Assessment Method and should not be confused with the engineering concept of Reliability, Availability, and Maintainability. The fundamental logic of RAM is based on a root-based aggregation function that integrates the weighted contributions of beneficial and non-beneficial criteria into an overall utility measure for each alternative. After normalization and weighting, the contributions of the benefit criteria and cost criteria are aggregated separately [26]. These aggregated components are then incorporated into the root-based ranking function defined in Eq. (24) to obtain the final RAM score (Ri) for alternative (i). The mathematical structure of RAM is designed so that stronger performance on beneficial criteria increases the overall utility of an alternative, whereas stronger exposure to non-beneficial or cost criteria reduces its relative desirability. Accordingly, (Ri) represents the overall utility of alternative (i) under the RAM aggregation mechanism. Alternatives are ranked in descending order of (Ri), and therefore, for any two alternatives (Aa) and (Ab), (Ra>Rb) implies that (Aa) is preferred to (Ab) under the adopted criterion weights and benefit–cost structure. Thus, the alternative with the highest (Ri) value is identified as the most preferred alternative. The original mathematical formulation and theoretical foundations of the method are provided by Sotoudeh-Anvari [25].

Firstly, m alternatives are determined. Opinions about alternatives of experts are collected regarding to criteria using linguistic variables in Table 1. Linguistic opinions are transformed into PFNs. Thus, PF-decision matrix is created. For the implementation of PF-RAM, the twelve evaluation criteria were divided into two groups according to their preference directions. The benefit criteria, for which higher performance is preferred, include LCA CO_2 Reduction Potential (LCA), Blend Compatibility (BCM), Fuel Supply Security (FSS), Supply Chain Reliability (SCR), Geopolitical Stability (GPS), Policy and Regulation Alignment (PRA), and Scalability Potential (SCP). In contrast, the cost criteria, for which lower values are preferred, include Direct Purchase Cost (DPC), Transportation and Distribution Cost (TDC), Infrastructure Needs (INF), Price Volatility Risk (PVR), and Number of Suppliers (NSP). After the individual expert evaluations were converted into Pythagorean fuzzy numbers and aggregated, the resulting evaluation of each alternative under each criterion was combined with the corresponding normalized criterion weight obtained from PF-SWARA. The weighted evaluations were then processed separately according to their benefit or cost orientation. The aggregated contributions of these two criterion groups were subsequently incorporated into the RAM ranking procedure to obtain the final ranking score for each procurement alternative. This treatment ensures that criteria with opposite preference directions are appropriately distinguished in the evaluation process and that their contributions are consistently reflected in the overall ranking. PF-decision values are calculated using Eq. (20), where $\tilde{b}_{ij}^{t}$ is the PFNs of criterion-j of alternative-i for expert-t.

$$\tilde{b}_{ij} = \left(\left(1 - \prod_{t=1}^{k}\left(1 - \alpha_{\tilde{b}_{ij}^{t}}^{2}\right)^{\frac{1}{k}}\right)^{0.5}, \prod_{t=1}^{k}\left(\beta_{\tilde{b}_{ij}^{t}}\right)^{\frac{1}{k}}\right) \quad (20)$$

Afterwards, PF-decision values are multiplied by the weights. The weighted decision values are computed with Eq. (21).

$$\tilde{y}_{ij} = w_j \tilde{b}_{ij} = \left(\left(1 - \left(1 - \alpha_{\tilde{b}_{ij}}^{2}\right)^{w_j}\right)^{0.5}, \left(\beta_{\tilde{b}_{ij}}\right)^{w_j}\right) \quad (21)$$

Later, the totals of weighted decision values according to types of criteria are established using Eqs. (22) and (23).

$$\tilde{\mathfrak{S}}_i^{+} = \sum_{j \in B} \tilde{y}_{ij} \quad (22)$$

$$\tilde{\mathfrak{S}}_i^{-} = \sum_{j \in C} \tilde{y}_{ij} \quad (23)$$

Finally, the ranking scores of alternatives are determined by Eq. (24).

$$\mathfrak{R}_i = \sqrt[\left(2 + \mathbb{S}'\left(\tilde{\mathfrak{S}}_i^{-}\right)\right)]{\left(2 + \mathbb{S}'\left(\tilde{\mathfrak{S}}_i^{+}\right)\right)} \quad (24)$$

To illustrate the PF-RAM calculation more transparently, PISAF can be considered as a complete example. First, the linguistic evaluations provided by the ten experts for PISAF under the twelve criteria were converted into their corresponding Pythagorean fuzzy numbers using the linguistic scale presented in Table 1. These individual evaluations were then aggregated to obtain a collective Pythagorean fuzzy evaluation for PISAF under each criterion. Subsequently, each aggregated evaluation was combined with the corresponding normalized criterion weight obtained from PF-SWARA, resulting in the weighted Pythagorean fuzzy values reported in Table 9. The weighted evaluations were then separated according to criterion orientation. LCA, BCM, FSS, SCR, GPS, PRA, and SCP were processed as benefit criteria, whereas DPC, TDC, INF, PVR, and NSP were processed as cost criteria. The resulting benefit and cost components were aggregated as reported in Table 10 and subsequently converted into the corresponding crisp values presented in Table 11. Finally, these values were incorporated into the RAM ranking procedure, producing a final score of 1.445 for PISAF, as reported in Table 12. Since higher RAM scores indicate more preferable alternatives, this value places PISAF first among the six evaluated SAF procurement strategies. This example provides a traceable connection between the original expert evaluations, the PF-SWARA criterion weights, the benefit and cost components, and the final RAM ranking result.

4. Analysis

This section includes the results of fuzzy decision-making for optimizing the sustainable aviation fuel (SAF) supply chain.

4.1. Weighting of Criteria

The evaluation criteria were identified through a structured multi-stage process. First, an extensive review of recent sustainable aviation fuel literature was conducted to compile a comprehensive list of potential evaluation criteria reported in previous studies. Similar or conceptually overlapping criteria were subsequently grouped into broader thematic categories, including economic, environmental, operational, and geopolitical dimensions. During this stage, duplicate indicators and highly similar concepts were consolidated to avoid unnecessary redundancy while preserving the comprehensiveness of the evaluation framework. The preliminary criteria set was then reviewed by the expert panel, who assessed the relevance, clarity, and practical applicability of each criterion from the perspective of commercial airline procurement decisions. Based on expert consensus, the final framework consisted of twelve evaluation criteria. Attention was given to ensuring that each criterion represented a distinct decision dimension with minimal conceptual overlap. Although certain criteria are naturally related, they capture different aspects of procurement decision making and were therefore retained as separate evaluation criteria. The criteria are shared in Table 2 with abbreviations and types.

Table 2
Criteria

Criterion	Type	Abb
Direct Production Cost	Min	DPC
Transport & Distribution Cost	Min	TDC
Infrastructure Investment	Min	INF
Price Volatility Risk	Min	PVR
LCA CO_2 Reduction Potential	Max	LCA
Blend Compatibility	Max	BCM
Feedstock Sustainability	Max	FSS
NOx, SOx, PM	Min	NSP
Supply Chain Reliability	Max	SCR
Geopolitical Stability	Max	GPS
Policy & Regulation Alignment	Max	PRA
Scalability Potential	Max	SCP

Although some of the twelve criteria are conceptually related, they were retained separately because they represent distinct sources of procurement performance and risk. This distinction is particularly important for Supply Chain Reliability (SCR), Geopolitical Stability (GPS), and Policy & Regulation Alignment (PRA). SCR captures the operational continuity and resilience of SAF supply, including the ability to maintain access to fuel under potential supply disruptions and the availability of diversified sourcing options. In contrast, GPS represents external country- or region-specific geopolitical conditions, including political instability, international conflicts, sanctions, and related uncertainties that may affect cross-border sourcing. PRA addresses a different institutional dimension by evaluating the compatibility of a procurement strategy with applicable regulations, policy incentives, carbon-related requirements, and frameworks such as ICAO CORSIA. Thus, geopolitical instability or regulatory change may influence supply reliability, but these criteria are not interchangeable: SCR reflects the resulting operational robustness of the supply arrangement, GPS captures exposure to geopolitical conditions, and PRA captures compatibility with the regulatory and policy environment. Maintaining these dimensions separately therefore enables the framework to distinguish operational, geopolitical, and institutional sources of procurement risk rather than combining them into a single broad risk criterion.

The criteria set used in this study is designed to capture the economic, environmental, technical, and strategic dimensions of sustainable aviation fuel supply chain management in a comprehensive manner. Economic and cost related criteria include the direct production cost per liter of SAF, which varies significantly across production pathways such as HEFA, Fischer–Tropsch, and Alcohol to Jet due to differences in process complexity and feedstock requirements. Logistics and distribution cost is another critical factor, influenced by the distance between refineries and airports as well as the choice of transportation modes such as pipelines, trucks, or tankers. Infrastructure investment requirements are also considered, as SAF deployment often requires additional investments in storage tanks, hydrant system adaptations, and blending facilities. In addition, long term price volatility risk is included to reflect the uncertainty arising from crude oil price dependency and fluctuations in biofuel feedstock markets. Environmental and technical emission criteria focus on lifecycle carbon emission reduction potential, as some SAF technologies can achieve emission reductions of 60 to 80 percent compared to conventional jet fuel. Compatibility with SAF blending ratios is evaluated in line with aircraft and engine manufacturer limits, including emerging targets of higher SAF blends. Feedstock sustainability is another key criterion, covering waste oils, agricultural residues, algae based oils, and synthetic fuel inputs, while also considering risks related to food competition and land use. Local emission reduction effects, such as decreases in NOx, SOx, and particulate matter, are assessed due to their impact on airport level environmental performance and carbon accreditation. Finally, geopolitical and strategic risk criteria address supply chain reliability through resilience against disruptions and access to diversified sourcing options, as well as country or regional geopolitical stability in terms of conflict, sanctions, and political uncertainty. Regulatory alignment and policy incentives are also included, reflecting compliance with SAF support schemes, carbon taxation, and ICAO CORSIA requirements. The final criterion captures long term production capacity and scalability, emphasizing the ability of SAF technologies to expand over time and ensure continuous feedstock availability.

The expert panel consisted of ten professionals with substantial experience in aviation, sustainable aviation fuels, energy systems, and strategic procurement. To ensure diversity of perspectives, the panel included participants from academia, the aviation industry, and energy-related organizations. Their professional backgrounds covered aviation management, sustainable energy systems, supply chain and procurement management, and sustainability-related decision making. Experts were selected through purposive sampling based on three predefined eligibility criteria: relevant professional or academic expertise in SAF or aviation-related decision making, familiarity with strategic procurement or supply chain processes, and at least ten years of relevant professional or academic experience. The participating experts had an average of approximately 17 years of relevant professional experience, indicating a high level of familiarity with the strategic, economic, environmental, and operational dimensions considered in the evaluation framework. Personal identities and institutional affiliations were not disclosed to preserve participant anonymity during the expert evaluation process. The linguistic opinions about criteria are shown in Table 3.

Table 3
Linguistic Opinions about Criteria

	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
1-Expert	H	H	ML	VL	AH	H	M	VVH	L	M	VH	VVH
2-Expert	M	H	M	VL	VH	H	M	VH	VL	H	H	VH
3-Expert	MH	MH	M	ML	VVH	VH	M	VVH	L	MH	H	H
4-Expert	M	MH	ML	VL	AH	VH	M	VVH	L	M	VH	H
5-Expert	MH	VH	M	VL	VH	VH	M	VH	VL	M	H	VVH
6-Expert	H	VH	M	VL	AH	VH	M	VH	VL	M	VH	VVH
7-Expert	H	MH	M	L	AH	MH	MH	VVH	L	H	H	H
8-Expert	MH	VH	ML	VL	VH	VH	M	VH	VL	M	H	VVH
9-Expert	H	VH	M	VL	VH	VH	MH	VH	L	H	H	H
10-Expert	M	H	ML	ML	VH	VH	MH	VH	VL	H	VH	H

Table 3 presents the individual linguistic evaluations provided by the ten experts for the twelve criteria. These individual assessments constitute the initial inputs of the PF-SWARA procedure and are subsequently converted into Pythagorean fuzzy numbers, as reported in Table 4. The individual PF evaluations are then aggregated across the experts according to the aggregation procedure described in the methodology, and the resulting collective PF values are presented in Table 5. Table 3 summarizes the aggregated expert evaluations obtained after combining the individual Pythagorean fuzzy judgments. These values constitute the primary input for the subsequent SWARA weighting procedure, as they reflect the collective perception of the expert panel regarding the relative importance of the evaluation criteria. The observed differences among the aggregated values indicate that the experts were able to distinguish meaningfully between the criteria before the weighting stage, thereby providing a consistent basis for the calculation of relative criterion importance. The linguistic opinions in Table 3 are converted to PFNs according to Table 1. Thus, PF-initial decision matrix is obtained and given in Table 4.

Table 4
PF-Initial Decision Matrix

Experts	DPC	TDC	INF	PVR	LCA	BCM
1-Expert	(0.7,0.45)	(0.7,0.45)	(0.4,0.7)	(0.2,0.85)	(0.95,0.2)	(0.7,0.45)
2-Expert	(0.5,0.6)	(0.7,0.45)	(0.5,0.6)	(0.2,0.85)	(0.8,0.35)	(0.7,0.45)
3-Expert	(0.6,0.55)	(0.6,0.55)	(0.5,0.6)	(0.4,0.7)	(0.85,0.3)	(0.8,0.35)
4-Expert	(0.5,0.6)	(0.6,0.55)	(0.4,0.7)	(0.2,0.85)	(0.95,0.2)	(0.8,0.35)
5-Expert	(0.6,0.55)	(0.8,0.35)	(0.5,0.6)	(0.2,0.85)	(0.8,0.35)	(0.8,0.35)
6-Expert	(0.7,0.45)	(0.8,0.35)	(0.5,0.6)	(0.2,0.85)	(0.95,0.2)	(0.8,0.35)
7-Expert	(0.7,0.45)	(0.6,0.55)	(0.5,0.6)	(0.3,0.75)	(0.95,0.2)	(0.6,0.55)
8-Expert	(0.6,0.55)	(0.8,0.35)	(0.4,0.7)	(0.2,0.85)	(0.8,0.35)	(0.8,0.35)
9-Expert	(0.7,0.45)	(0.8,0.35)	(0.5,0.6)	(0.2,0.85)	(0.8,0.35)	(0.8,0.35)
10-Expert	(0.5,0.6)	(0.7,0.45)	(0.4,0.7)	(0.4,0.7)	(0.8,0.35)	(0.8,0.35)
Experts	FSS	NSP	SCR	GPS	PRA	SCP
1-Expert	(0.5,0.6)	(0.85,0.3)	(0.3,0.75)	(0.5,0.6)	(0.8,0.35)	(0.85,0.3)
2-Expert	(0.5,0.6)	(0.8,0.35)	(0.2,0.85)	(0.7,0.45)	(0.7,0.45)	(0.8,0.35)
3-Expert	(0.5,0.6)	(0.85,0.3)	(0.3,0.75)	(0.6,0.55)	(0.7,0.45)	(0.7,0.45)
4-Expert	(0.5,0.6)	(0.85,0.3)	(0.3,0.75)	(0.5,0.6)	(0.8,0.35)	(0.7,0.45)
5-Expert	(0.5,0.6)	(0.8,0.35)	(0.2,0.85)	(0.5,0.6)	(0.7,0.45)	(0.85,0.3)
6-Expert	(0.5,0.6)	(0.8,0.35)	(0.2,0.85)	(0.5,0.6)	(0.8,0.35)	(0.85,0.3)
7-Expert	(0.6,0.55)	(0.85,0.3)	(0.3,0.75)	(0.7,0.45)	(0.7,0.45)	(0.7,0.45)
8-Expert	(0.5,0.6)	(0.8,0.35)	(0.2,0.85)	(0.5,0.6)	(0.7,0.45)	(0.85,0.3)
9-Expert	(0.6,0.55)	(0.8,0.35)	(0.3,0.75)	(0.7,0.45)	(0.7,0.45)	(0.7,0.45)
10-Expert	(0.6,0.55)	(0.8,0.35)	(0.2,0.85)	(0.7,0.45)	(0.8,0.35)	(0.7,0.45)

Afterwards, PF-aggregated values are calculated using Eq. (15). Next, the PF-aggregated values are defuzzified with Eq. (16). The results are presented in Table 5.

Table 5
Aggregated Values

	DPC	TDC	INF	PVR	LCA	BCM
PF-Agg	(0.622,0.521)	(0.725,0.432)	(0.464,0.638)	(0.265,0.807)	(0.89,0.276)	(0.769,0.385)
Agg	0.558	0.669	0.404	0.209	0.858	0.721
	FSS	NSP	SCR	GPS	PRA	SCP
PF-Agg	(0.534,0.585)	(0.822,0.329)	(0.256,0.798)	(0.606,0.53)	(0.746,0.407)	(0.784,0.373)
Agg	0.472	0.784	0.214	0.543	0.695	0.737

The aggregated values are sorted in descending. Next, differences between the crisped values and the previous values are computed. Then, coefficients of criteria are established by Eq. (17). Recalculated values are obtained with the help of Eq. (18). Finally, the weights of criteria are defined as Eq. (19). The results are presented in Table 6.

Table 6
Relative, Coefficient, Recalculated and Weights of Criteria

Criteria	Agg	Relative	Coefficient	Recalculated	Weight
LCA	0.858		1	1	0.108
NSP	0.784	0.074	1.074	0.931	0.100
SCP	0.737	0.046	1.046	0.890	0.096
BCM	0.721	0.016	1.016	0.876	0.094
PRA	0.695	0.026	1.026	0.853	0.092
TDC	0.669	0.026	1.026	0.832	0.090
DPC	0.558	0.111	1.111	0.748	0.081
GPS	0.543	0.015	1.015	0.737	0.079
FSS	0.472	0.072	1.072	0.688	0.074
INF	0.404	0.068	1.068	0.645	0.069
SCR	0.214	0.190	1.190	0.542	0.058
PVR	0.209	0.005	1.005	0.539	0.058

As can be seen from Table 6, the analysis indicates that environmental performance criteria play a dominant role in the performance of the sustainable aviation fuel supply chain. In particular, the LCA CO_2 reduction potential emerges as the most important criterion with a weight of 0.108, highlighting the central importance of lifecycle emission reductions in strategic SAF related decision making. This finding reflects the growing pressure on the aviation sector to achieve substantial carbon reductions in line with international climate targets. In addition, local emission reduction indicators, including NOx, SOx, and particulate matter, rank as the second most important criterion with a weight of 0.100. The high importance assigned to these pollutants emphasizes the relevance of air quality improvements at the airport and regional level, as well as their contribution to broader environmental and regulatory objectives. Together, these results suggest that environmental and emission related considerations outweigh purely economic or logistical factors when evaluating SAF supply chain strategies, underlining the strategic role of sustainability driven criteria in contemporary aviation fuel decision frameworks.

4.2. Ranking of Strategic Procurement Approaches

The procurement alternatives were identified through a structured screening process combining evidence from the sustainable aviation fuel literature and expert consultation. Initially, a broader list of procurement practices and sourcing options was compiled from previous studies. Similar alternatives were subsequently consolidated based on their underlying procurement logic rather than their technological characteristics. The objective was to identify mutually distinguishable procurement strategies that represent alternative sourcing approaches available to commercial airlines. Consequently, the final framework consists of six procurement strategies reflecting different contractual structures, investment models, supplier configurations, and feedstock sourcing approaches. The selected procurement strategies are intended to represent realistic strategic sourcing options currently discussed or adopted within the aviation industry rather than hypothetical alternatives developed solely for analytical purposes. They reflect the principal procurement approaches reported in the sustainable aviation fuel literature and evaluated by industry experts participating in this study. Although the availability and implementation of these strategies may differ across airlines and geographical regions, they collectively capture the major procurement pathways currently considered by commercial airlines during the transition toward sustainable aviation fuels. These strategic procurement approaches are illustrated in Table 7 with abbreviations.

Table 7
Strategic Procurement Approaches

Strategic Procurement Approach	Abb
Long-Term Supply Agreement with Local (Domestic) SAF Producers	LTSAF
International Diversified SAF Supply Strategy	IDSAF
Partnership/Investment in SAF Production Facilities	PISAF
Focus on Waste-Based SAF Technologies	WBSAF
Collaboration with E-SAF / Power-to-Liquid (PtL) Producers	ESAPL
Airport-Based Shared SAF Platforms	ABSPM

The strategic alternatives considered in this study represent different approaches to securing sustainable aviation fuel supply under varying economic, operational, and risk conditions. The first alternative focuses on long term supply agreements with domestic SAF producers, which generally offer lower logistics costs and reduced supply risk due to geographical proximity, although production capacity may remain limited in some countries. This approach is widely applied in regions where domestic SAF production facilities are already established. The second alternative involves an international diversified SAF sourcing strategy, in which supply is secured from multiple foreign producers. This strategy helps distribute geopolitical risk and supports long term supply security, but it may result in higher logistics and transportation costs, and it is therefore more common among multinational airlines. The third alternative is vertical integration through equity investment or partnership in SAF production facilities, often referred to in the literature as a SAF offtake agreement combined with equity participation. This strategy can significantly reduce price volatility and enhance supply security, although it requires substantial capital investment. The fourth alternative emphasizes a shift toward waste based SAF technologies, such as HEFA pathways using used cooking oil or municipal waste. These options offer lower emissions and improved feedstock sustainability, but they are constrained by limited feedstock availability. The fifth alternative involves collaboration with e SAF or power to liquid producers that synthesize SAF using renewable electricity, delivering very low lifecycle emissions despite currently high production costs, and this pathway is expected to play a central role in the European Union's post 2030 aviation strategy. The final alternative considers airport based SAF consortium models, where multiple airlines jointly create demand to stimulate SAF supply, enabling economies of scale and shared infrastructure investments, while also introducing higher coordination and governance complexity. Opinions about strategic procurement approaches of experts are collected regarding criteria using linguistic variables in Table 1. The linguistic opinions about strategic procurement approaches are displayed in Table A1. Linguistic opinions are transformed into PFNs. Thus, PF-decision matrix is created using Eq. (20). PF-decision matrix is exhibited in Table 8.

Table 8
PF-Decision Matrix

	DPC	TDC	INF	PVR	LCA	BCM
LTSAF	(0.763,0.393)	(0.717,0.441)	(0.701,0.454)	(0.692,0.464)	(0.432,0.662)	(0.394,0.692)
IDSAF	(0.602,0.536)	(0.651,0.496)	(0.611,0.532)	(0.63,0.516)	(0.477,0.633)	(0.468,0.642)
PISAF	(0.558,0.568)	(0.602,0.536)	(0.622,0.521)	(0.63,0.516)	(0.63,0.516)	(0.651,0.496)
WBSAF	(0.899,0.263)	(0.896,0.267)	(0.899,0.263)	(0.901,0.259)	(0.26,0.803)	(0.312,0.763)
ESAPL	(0.775,0.377)	(0.746,0.407)	(0.766,0.387)	(0.735,0.417)	(0.444,0.658)	(0.454,0.648)
ABSPM	(0.746,0.407)	(0.77,0.385)	(0.83,0.322)	(0.8,0.355)	(0.364,0.72)	(0.344,0.73)
	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	(0.422,0.672)	(0.717,0.441)	(0.432,0.662)	(0.432,0.662)	(0.359,0.718)	(0.381,0.703)
IDSAF	(0.529,0.598)	(0.63,0.516)	(0.468,0.642)	(0.502,0.622)	(0.567,0.573)	(0.454,0.648)
PISAF	(0.594,0.541)	(0.626,0.515)	(0.572,0.557)	(0.619,0.527)	(0.611,0.532)	(0.619,0.527)
WBSAF	(0.334,0.752)	(0.884,0.278)	(0.323,0.758)	(0.33,0.748)	(0.323,0.758)	(0.312,0.763)
ESAPL	(0.444,0.658)	(0.766,0.387)	(0.444,0.658)	(0.464,0.638)	(0.454,0.648)	(0.454,0.648)
ABSPM	(0.355,0.725)	(0.813,0.341)	(0.374,0.715)	(0.323,0.74)	(0.344,0.73)	(0.355,0.725)

Afterwards, values in Table 8 are multiplied by the weight values of criteria via Eq. (21). The weighted decision matrix is expressed in Table 9.

Table 9
Weighted Decision Matrix

	DPC	TDC	INF	PVR	LCA	BCM
LTSAF	(0.299,0.904)	(0.264,0.921)	(0.25,0.927)	(0.244,0.93)	(0.137,0.963)	(0.122,0.968)
IDSAF	(0.218,0.935)	(0.232,0.932)	(0.209,0.941)	(0.216,0.94)	(0.153,0.959)	(0.148,0.961)
PISAF	(0.199,0.941)	(0.21,0.939)	(0.214,0.939)	(0.216,0.94)	(0.213,0.941)	(0.219,0.939)
WBSAF	(0.403,0.866)	(0.387,0.876)	(0.382,0.88)	(0.382,0.88)	(0.08,0.98)	(0.096,0.976)
ESAPL	(0.307,0.9)	(0.28,0.914)	(0.285,0.913)	(0.266,0.921)	(0.141,0.962)	(0.143,0.962)
ABSPM	(0.29,0.908)	(0.294,0.909)	(0.326,0.897)	(0.303,0.907)	(0.114,0.97)	(0.106,0.972)
	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	(0.125,0.968)	(0.236,0.937)	(0.123,0.97)	(0.119,0.972)	(0.089,0.981)	(0.095,0.98)
IDSAF	(0.162,0.959)	(0.198,0.949)	(0.135,0.968)	(0.141,0.968)	(0.15,0.968)	(0.115,0.975)
PISAF	(0.186,0.952)	(0.197,0.949)	(0.17,0.957)	(0.182,0.956)	(0.164,0.964)	(0.166,0.963)
WBSAF	(0.097,0.977)	(0.337,0.903)	(0.09,0.98)	(0.089,0.98)	(0.08,0.984)	(0.077,0.984)
ESAPL	(0.133,0.967)	(0.26,0.927)	(0.127,0.969)	(0.129,0.969)	(0.116,0.975)	(0.115,0.975)
ABSPM	(0.104,0.974)	(0.287,0.918)	(0.105,0.975)	(0.087,0.979)	(0.086,0.982)	(0.088,0.981)

Later, weighted decision values according to types of criteria are summed using Eqs. (22) and (23). The results are illustrated in Table 10.

Table 10
Total Weighted Decision Values

	$\tilde{\mathfrak{S}}_i^+$		$\tilde{\mathfrak{S}}_i^-$	
LTSAF	0.304	0.817	0.543	0.673
IDSAF	0.370	0.781	0.459	0.731
PISAF	0.470	0.715	0.444	0.740
WBSAF	0.229	0.869	0.735	0.531
ESAPL	0.334	0.799	0.579	0.641
ABSPM	0.259	0.846	0.613	0.616

After that, the total weighted values are defuzzified using normalized score function. The crisped total weighted values are displayed in Table 11.

Table 11
Crisped Total Weighted Values

	$\mathbb{S}'(\tilde{\mathfrak{S}}_i^+)$	$\mathbb{S}'(\tilde{\mathfrak{S}}_i^-)$
LTSAF	0.212	0.421
IDSAF	0.263	0.338
PISAF	0.354	0.325
WBSAF	0.148	0.629
ESAPL	0.236	0.462
ABSPM	0.176	0.498

Finally, the ranking scores of strategic procurement approaches are determined by Eq. (24). The ranking scores are summarized in Table 12.

Table 12
Ranking Scores

	$\mathfrak{R}$
LTSAF	1.388
IDSAF	1.418
PISAF	1.445
WBSAF	1.338
ESAPL	1.387
ABSPM	1.365

The first-place ranking of partnership or investment in SAF production facilities (PISAF), with an R value of 1.445, should be interpreted in relation to the multidimensional evaluation structure rather than as the result of a single advantage. In particular, the result is consistent with the high importance assigned to environmental performance, scalability, and regulatory alignment in the criteria-weighting stage. Lifecycle CO_2 reduction potential and local emission reduction received the two highest criterion weights, while scalability potential and policy and regulation alignment were also among the most influential considerations. From a managerial perspective, direct participation in SAF production can provide airlines with greater influence over technology and production pathways, facilitate longer-term alignment between production capacity and sustainability targets, and improve control over future supply availability. It can also strengthen supply security and reduce exposure to price volatility by establishing closer and more stable relationships with SAF producers. However, these benefits involve important trade-offs. Partnership or direct investment requires substantial capital commitments, creates greater exposure to project and technology risks, and may reduce procurement flexibility compared with diversified or contract-based sourcing strategies. Therefore, the first-place position of PISAF should not be interpreted as indicating that it dominates every individual criterion or is universally optimal for all airlines. Rather, it indicates that, according to the participating experts and the adopted criterion weights, its combined environmental, scalability, supply-security, and strategic benefits provide the strongest overall balance among the evaluated procurement alternatives despite its investment-related disadvantages.

4.3. Sensitivity Analysis

A one-at-a-time sensitivity analysis was conducted to examine the stability of the alternative rankings with respect to changes in the criterion weights obtained from the PF-SWARA procedure. In each scenario, the final weight of one criterion was increased or decreased by 10% relative to its baseline value, while the weights of all remaining criteria were kept unchanged. For example, if the baseline weight of a criterion is (wj), the corresponding sensitivity scenarios use (1.10wj) and (0.90wj), respectively. The ±10% range was selected to represent a moderate and symmetric perturbation around the baseline weights, allowing the robustness of the rankings to be evaluated without imposing extreme deviations from the expert-derived weighting structure. Each criterion was modified separately so that its individual influence on the final ranking could be observed. The modified weights were directly introduced into the ranking calculation, and the remaining criterion weights were not re-estimated through PF-SWARA. Accordingly, the analysis should be interpreted as a local one-at-a-time robustness test rather than as a complete re-estimation of the weighting model. The resulting rankings were then compared with the baseline ranking to determine whether moderate variations in individual criterion importance altered the prioritization of the strategic procurement alternatives. The detailed findings of the sensitivity analysis are presented in Table 13, offering a clear overview of how stable the strategic procurement rankings remain under moderate variations in the evaluation parameters.

Table 13
Sensitivity Analysis

	DPC +10%	TDC +10%	INF +10%	PVR +10%	LCA +10%	BCM +10%
LTSAF	1.387	1.387	1.387	1.387	1.389	1.389
IDSAF	1.417	1.417	1.417	1.417	1.419	1.419
PISAF	1.444	1.444	1.444	1.444	1.447	1.447
WBSAF	1.337	1.337	1.337	1.337	1.338	1.338
ESAPL	1.385	1.386	1.386	1.386	1.388	1.388
ABSPM	1.364	1.364	1.364	1.364	1.366	1.366
	DPC -10%	TDC -10%	INF -10%	PVR -10%	LCA -10%	BCM -10%
LTSAF	1.390	1.389	1.389	1.389	1.387	1.387
IDSAF	1.419	1.419	1.419	1.419	1.417	1.417
PISAF	1.447	1.447	1.447	1.447	1.444	1.444
WBSAF	1.339	1.338	1.338	1.338	1.337	1.337
ESAPL	1.388	1.388	1.388	1.388	1.386	1.386
ABSPM	1.366	1.366	1.366	1.366	1.364	1.364
	FSS +10%	NSP +10%	SCR +10%	GPS +10%	PRA +10%	SCP +10%
LTSAF	1.389	1.387	1.389	1.389	1.389	1.389
IDSAF	1.419	1.417	1.419	1.419	1.419	1.419
PISAF	1.446	1.444	1.446	1.446	1.446	1.446
WBSAF	1.338	1.337	1.338	1.338	1.338	1.338
ESAPL	1.387	1.386	1.387	1.387	1.387	1.387
ABSPM	1.366	1.364	1.366	1.366	1.366	1.366
	FSS -10%	NSP -10%	SCR -10%	GPS -10%	PRA -10%	SCP -10%
LTSAF	1.387	1.389	1.387	1.387	1.388	1.388
IDSAF	1.417	1.419	1.417	1.417	1.417	1.418
PISAF	1.444	1.446	1.445	1.444	1.445	1.445
WBSAF	1.337	1.338	1.337	1.337	1.337	1.337
ESAPL	1.386	1.388	1.386	1.386	1.386	1.386
ABSPM	1.364	1.366	1.364	1.364	1.364	1.364

When Table 13 is examined in detail, it can be observed that the rankings of the strategic procurement approaches remain unchanged under all criterion-based variations. This finding indicates that the proposed decision-making model produces highly stable results, as changes in the individual criteria do not affect the identification of the optimal strategic procurement approach. In other words, the best performing strategy maintains its leading position even when the relative importance of the evaluation criteria is adjusted within the defined range. This robustness strengthens the validity and credibility of the analysis outcomes.

In addition to the sensitivity analysis, a second ranking method is employed to further assess the reliability of the results. The COPRAS method was selected as a validation technique because it is based on a utility-oriented decision-making philosophy that evaluates alternatives by simultaneously maximizing beneficial criteria and minimizing non-beneficial criteria through proportional assessment. Unlike ranking approaches that rely primarily on pairwise dominance or outranking relationships, COPRAS estimates the relative utility degree of each alternative, thereby providing an independent assessment of overall performance. Since both RAM and COPRAS explicitly accommodate benefit and cost criteria while employing different computational mechanisms for ranking alternatives, their combined application enables methodological triangulation. Consequently, the consistency of the rankings obtained from these conceptually different methods provides stronger evidence regarding the robustness and reliability of the proposed decision-making framework. The outcomes obtained from the COPRAS analysis are visually presented in Figure 2, allowing for a clear and intuitive comparison of the strategic procurement alternatives.

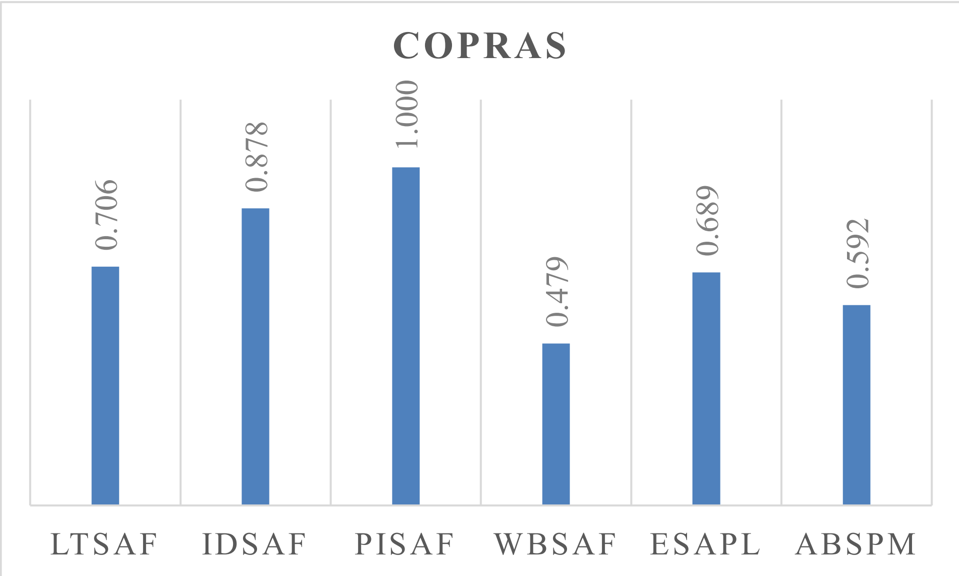

Fig. 2. COPRAS Results

When the results obtained from the RAM and COPRAS methods are compared, a very high level of consistency between the two ranking approaches is observed. Specifically, the Pearson correlation coefficient between the RAM and COPRAS results is 0.997, indicating a very strong linear association between the performance scores generated by the two methods. In addition, the Spearman rank correlation coefficient is equal to 1, confirming that the ordering of the strategic procurement approaches is identical under RAM and COPRAS. These findings provide strong evidence of methodological consistency between the two approaches and support the robustness of the obtained ranking within the scope of this comparative analysis. However, the high correlations should not be interpreted as evidence of complete method independence, since RAM and COPRAS represent two specific MCDM approaches with their own computational structures and assumptions. Therefore, the comparison provides cross-method validation of the ranking results rather than demonstrating that the findings would necessarily remain unchanged under all alternative decision-making methods.

To provide additional cross-method validation, the alternative rankings obtained from PF-RAM were compared with those generated by COPRAS using the same decision context and criterion-weighting structure. The complete numerical COPRAS results are now reported in Table 13, including the final performance value and rank of each procurement alternative. The degree of agreement between the RAM and COPRAS results was subsequently evaluated using both Pearson and Spearman correlation coefficients. The Pearson coefficient was calculated using the numerical performance values generated by the two methods and reached 0.997, indicating a very strong positive association between their results. The Spearman coefficient was calculated using the corresponding alternative ranks and reached 1.000, indicating identical ordering of the six procurement alternatives. These findings provide strong evidence of cross-method consistency and support the robustness of the ranking with respect to the two MCDM procedures considered. However, they should not be interpreted as evidence of general method independence, since the comparison is restricted to RAM and COPRAS and does not establish that the same results would necessarily be obtained using other MCDM methods.

5. Discussion

The discussion is organized around the four major themes identified in the literature review, namely economic considerations, environmental performance, operational and supply chain factors, and procurement strategy selection. This structure enables the findings of the present study to be interpreted in relation to previous research while highlighting the additional insights generated from the perspective of commercial airline procurement decisions.

Life cycle carbon emission assessment is the most important criterion in increasing the efficiency of the sustainable aviation fuel (SAF) supply chain. Life cycle assessment can measure the environmental impact of SAF from raw material procurement to the production process, including material supply, production, use, and recycling [27]. Indeed, while new aircraft technologies have the potential to reduce the carbon footprint of aviation, sustainable aviation fuel can be considered a short-to-medium-term solution for decarbonizing the aviation sector. Compared to fossil fuels, SAF has a lower carbon emission footprint and provides environmental benefits while being produced from renewable biological materials [28]. In this context, Zhang *et al.* [29] focus on carbon emissions during the storage and transportation phases of SAF in their study. Considering the fundamental differences between SAF and conventional jet fuel, they examine the potential risks associated with the use of SAF under practical applications. As a result, a 92% SAF blend reduces carbon emissions by 78.5% compared to jet fuel. The local emission reduction effect is the second most important criterion in increasing the supply chain efficiency of SAF. This is because the emission reduction effect and fuel efficiency improvement strategies maximize profit [30].

Partnering with or investing in a sustainable aviation fuel (SAF) production facility is a significant alternative for increasing the efficiency of the sustainable aviation fuel supply chain. Such investments reduce price volatility and ensure supply security. Additionally, market incentives such as cooperation, regulations, and financial support are crucial for promoting SAF production [31]. In other words, to effectively scale SAF, stakeholders and governments should enable new business models and encourage consumer participation. This aims to increase SAF production capacity. Uddin *et al.* [32] integrate various ethanol feedstock approaches and comprehensive strategies within consistent frameworks, enabling a direct comparison of technology options and optimal SAF production solutions. On the other hand, Peters *et al.* [33] aim to provide an overview of the current state of aviation biofuel production. In this context, it examines various routes and technologies, focusing on existing commercial routes, both approved and unapproved, by the aviation industry. Although partnership or investment in SAF production facilities emerged as the highest-ranked procurement strategy within the proposed decision framework, this result should be interpreted within the context of the expert-based evaluation adopted in the present study. The ranking does not constitute empirical evidence that this strategy is universally superior across all market conditions or organizational settings. Rather, it reflects the collective assessment of the participating experts under the defined evaluation criteria. Future studies incorporating real procurement outcomes and operational performance data would provide valuable external validation of the proposed prioritization.

Compared with previous studies, the present research extends the sustainable aviation fuel literature by shifting the focus from production technologies and environmental assessments toward procurement decision making from the perspective of commercial airlines. Rather than evaluating isolated technological or environmental aspects, the proposed framework simultaneously incorporates economic, environmental, operational, and geopolitical considerations into a unified procurement decision model. Consequently, the study contributes not only by identifying the most appropriate procurement strategy but also by demonstrating how multiple strategic considerations can be integrated into a practical decision support framework for airline managers. The strategic implications presented in this study should be interpreted as decision support recommendations rather than prescriptive solutions. Since the prioritization results are derived from expert evaluations within the proposed multi-criteria decision-making framework, their applicability may vary depending on organizational objectives, market conditions, regulatory developments, and technological progress. Therefore, the findings are intended to support managerial judgment rather than replace it. The robustness of the proposed framework should be interpreted within the scope of the analyses conducted in this study. The consistency observed between the RAM and COPRAS rankings provides supporting evidence for the stability of the obtained results. However, broader validation using alternative datasets, additional expert panels, and real-world procurement outcomes would further strengthen the generalizability of the proposed decision-support framework.

6. Conclusion

The transition toward sustainable aviation fuel creates a complex strategic procurement problem for commercial airlines because economic feasibility, environmental performance, operational reliability, regulatory requirements, and long-term supply security must be considered simultaneously. To address this challenge, this study developed an integrated decision-support framework combining Pythagorean fuzzy sets, SWARA, and RAM to prioritize SAF procurement strategies under uncertainty. The findings indicate that lifecycle CO_2 reduction potential is the most important evaluation criterion, with a weight of 0.108, followed by local emission reduction, with a weight of 0.100. These results demonstrate the central role of environmental performance in strategic SAF procurement decisions. Among the evaluated procurement alternatives, partnership or investment in SAF production facilities (PISAF) achieved the highest-ranking score of 1.445 and emerged as the most preferred strategy according to the participating experts and the adopted evaluation structure. This result suggests that closer participation in SAF production can provide an attractive overall balance between sustainability objectives, long-term supply considerations, scalability, and strategic control, although its capital requirements and investment risks should also be considered. The sensitivity analysis and comparison with COPRAS further supported the stability and methodological consistency of the obtained ranking results.

Despite these contributions, several limitations should be considered when interpreting the findings. First, the framework relies primarily on expert judgments and therefore reflects the knowledge and perceptions of a relatively limited expert panel rather than observed procurement behavior. Second, the criteria and alternatives represent the current SAF market, technological, and regulatory environment and may require revision as the industry develops. Third, the model does not incorporate organization-specific procurement data or dynamic market indicators such as actual SAF prices, production capacity, feedstock availability, transportation costs, and regulatory changes. Finally, the findings are influenced by the assumptions and computational structures of the selected Pythagorean fuzzy SWARA–RAM framework. Future research should therefore validate the proposed prioritization using real procurement and investment data from commercial airlines and SAF producers. Larger and more geographically and professionally diverse expert panels could also be employed to examine the generalizability of the findings. Integrating dynamic market indicators would enable the framework to respond more effectively to changing SAF market conditions. Future studies could additionally compare the results with alternative MCDM weighting and ranking approaches, as well as other fuzzy and non-fuzzy uncertainty representations, to further assess methodological robustness. These extensions would strengthen the external validity, adaptability, and practical applicability of the proposed decision-support framework.

Appendix

Table A1
Linguistic Opinions about Strategic Procurement Approaches

	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	VH	MH	H	VH	M	M	ML	VH	L	L	ML	L
IDSAF	H	H	M	M	ML	ML	M	MH	ML	ML	MH	ML
PISAF	MH	H	MH	H	H	M	MH	H	MH	H	MH	MH
WBSAF	AH	AH	VVH	VVH	L	L	VL	VH	L	ML	VL	VL
ESAPL	VH	VH	H	H	ML	ML	M	VH	M	ML	ML	ML
ABSPM	VH	H	VVH	VVH	ML	L	L	VVH	ML	L	L	L
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	VH	VH	VH	MH	M	M	L	VH	ML	M	L	L
IDSAF	MH	M	MH	MH	M	ML	MH	MH	ML	M	M	M
PISAF	M	M	H	MH	MH	H	H	M	M	M	MH	M
WBSAF	AH	VVH	VVH	AH	L	ML	L	VVH	ML	ML	ML	ML
ESAPL	VH	H	H	H	M	ML	ML	VH	ML	M	M	M
ABSPM	H	VH	VVH	H	L	ML	ML	H	ML	L	ML	L
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	VH	VH	MH	MH	M	L	L	MH	L	M	ML	M
IDSAF	M	H	M	H	M	ML	ML	M	MH	M	MH	ML
PISAF	H	MH	H	H	H	H	MH	H	H	MH	MH	MH
WBSAF	VVH	VVH	AH	AH	VL	L	ML	VVH	VL	ML	ML	L
ESAPL	H	H	VH	VH	M	ML	M	VH	M	M	M	M
ABSPM	H	H	VVH	H	L	L	ML	VVH	ML	ML	ML	L
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	MH	MH	VH	H	L	L	M	H	M	M	L	L
IDSAF	M	H	MH	MH	ML	M	MH	MH	ML	M	ML	M
PISAF	M	H	M	MH	MH	H	H	M	M	MH	M	MH
WBSAF	AH	AH	AH	VVH	ML	VL	ML	VVH	VL	VL	L	L
ESAPL	VH	H	VH	VH	M	M	M	H	ML	M	ML	M
ABSPM	VH	VH	VVH	VVH	ML	ML	L	H	ML	L	L	ML
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	VH	MH	H	MH	M	ML	M	H	M	M	M	M
IDSAF	H	MH	H	MH	ML	M	MH	H	ML	MH	MH	ML
PISAF	MH	M	M	MH	MH	MH	M	M	M	MH	H	H
WBSAF	VVH	AH	VVH	VVH	L	ML	VL	AH	ML	L	VL	ML
ESAPL	VH	VH	H	H	ML	M	ML	VH	ML	ML	ML	ML
ABSPM	H	VH	H	VH	ML	ML	ML	VH	L	L	ML	L

Table A1
Continued

	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	H	VH	MH	H	ML	M	ML	VH	M	ML	L	ML
IDSAF	MH	H	H	MH	M	ML	ML	H	ML	MH	MH	ML
PISAF	M	MH	MH	MH	M	H	M	H	MH	M	MH	MH
WBSAF	VVH	VH	VH	VH	VL	L	L	VH	ML	L	ML	L
ESAPL	VH	H	VH	H	ML	ML	ML	H	ML	M	M	M
ABSPM	H	H	VVH	VH	ML	ML	L	VVH	L	L	L	ML
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	VH	H	H	H	L	L	M	MH	L	L	ML	L
IDSAF	M	M	H	H	M	MH	M	MH	M	ML	MH	M
PISAF	M	M	MH	H	MH	M	M	H	M	H	M	H
WBSAF	VH	VVH	VH	AH	VL	L	ML	VH	L	L	VL	VL
ESAPL	H	VH	H	H	ML	M	ML	H	M	ML	ML	ML
ABSPM	H	H	VVH	VVH	L	L	L	VVH	ML	L	L	ML
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	VH	MH	H	MH	ML	L	ML	MH	ML	ML	L	L
IDSAF	MH	H	MH	H	MH	ML	MH	M	M	ML	MH	M
PISAF	M	H	H	H	H	H	H	M	M	H	H	MH
WBSAF	VH	VH	AH	AH	VL	VL	ML	AH	L	L	L	ML
ESAPL	VH	VH	VH	VH	M	M	ML	H	M	M	M	M
ABSPM	VH	VVH	VH	VVH	ML	L	ML	VH	L	L	L	ML
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	MH	VH	MH	H	M	ML	M	MH	M	L	L	ML
IDSAF	H	MH	M	H	M	M	M	H	M	ML	M	M
PISAF	M	MH	M	M	M	MH	M	H	H	MH	M	M
WBSAF	AH	VH	VVH	VVH	VL	VL	VL	AH	ML	ML	L	VL
ESAPL	H	H	VH	H	ML	M	ML	VH	ML	M	ML	ML
ABSPM	H	H	VVH	VH	ML	L	L	VH	ML	ML	L	L
	DPC	TDC	INF	PVR	LCA	BCM	FSS	NSP	SCR	GPS	PRA	SCP
LTSAF	VH	H	H	VH	L	L	L	VH	M	M	L	ML
IDSAF	M	H	MH	M	ML	M	M	H	M	MH	MH	ML
PISAF	MH	M	H	M	H	H	M	MH	M	MH	H	H
WBSAF	VVH	AH	AH	VVH	VL	ML	ML	VVH	VL	VL	ML	L
ESAPL	VH	H	VH	H	ML	ML	M	VH	ML	ML	M	ML
ABSPM	VH	VVH	VH	H	L	L	ML	VVH	ML	L	ML	ML

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Conflicts of Interest
The authors declare no conflicts of interest.

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