

article category : Logistic Management

Selecting Green Suppliers Using a Hybrid Fuzzy BWM and IVIF-MABAC Approach in the Tropical Fruit Sector

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ARTICLE INFORMATION

Article history:

Received: August 01, 2025
Revised: September 03, 2025
Accepted: December 15, 2025

Keywords:

Green Suppliers Selection
F-BWM
IVIF-MABAC
Sustainability
Tropical Fruit Industry

ABSTRACT

Agribusiness companies face challenges in green supplier selection due to subjective judgments and information gaps. To address these linguistic ambiguity and subjective uncertainties, this study develops a hybrid MCDM framework integrating the α -cut based Fuzzy BWM and Interval-Valued Intuitionistic Fuzzy MABAC (IVIF-MABAC). F-BWM α -cut derives stable weights from linguistic preferences, and IVIF-MABAC provides robust ranking by handling hesitancy. This approach, novel for the Indonesian tropical fruit sector, involved three experts (academic, manager, consultant) via questionnaires and FGDs. Results show Product Quality and Transparency & Traceability are critical. The 4th Green Supplier consistently achieved the highest ranking. The framework offers managers a reliable tool, enhancing sustainability and competitiveness within tropical fruit supply chains.

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INTRODUCTION

Sustainability has emerged as a strategic imperative in agri-food supply chains, driven by intensifying regulatory mandates and heightened consumer demands for operational transparency [1], [2], [3]. The tropical fruit sector—characterized by high perishability and heterogeneous production—faces unique challenges that necessitate robust digital traceability to maintain quality and food safety [3],[4]. Consequently, identifying suppliers capable of simultaneously fulfilling economic, social, and environmental mandates has emerged as a critical strategic priority for agribusinesses [5],[6],[7].

While various multi-criteria decision-making (MCDM) methods are applied to sustainable supplier selection traditional deterministic and conventional fuzzy approaches often struggle to address linguistic ambiguity and expert inconsistency [8], [9]. Established techniques like AHP and Delphi face significant challenges, including high comparison loads and unstable weight estimations [10]. These constraints highlight a critical research gap: the need for a robust, adaptive framework that integrates fuzzy weighting with interval-valued ranking to simultaneously manage subjective hesitation and data variability [11], [8], [12]. This is particularly pertinent in the tropical fruit sector, where evaluations are frequently hampered by limited field data and highly uncertain expert assessments.

Based on this gap, this study proposes a hybrid framework that integrates the α -cut based Fuzzy Best Worst Method (F-BWM α -cut) with the Interval-Valued Intuitionistic Fuzzy MABAC (IVIF-MABAC). F-BWM α -cut improves cognitive efficiency, reduces comparison burden, and ensures more consistent weight generation by allowing experts to express preferences

linguistically, which are then transformed into stable numerical intervals [13], [14]. Meanwhile, IVIF-MABAC accommodates membership, non-membership, and hesitation degrees simultaneously, leading to more reliable rankings in complex decision environments [15], [16]. The integration of these two methods is highly suited to the characteristics of tropical fruit supply chains, which are fraught with uncertainty, such as seasonal fluctuations in quality, differences in cultivation practices between farmers, and limited documentation at the supplier level. Therefore, methods that accommodate uncertainty and ambiguity in expert assessments are more effective in supporting sustainable supplier selection decisions.

This study delivers three primary contributions. First, it introduces a hybrid MCDM framework that manages linguistic ambiguity and uncertainty. Second, it establishes a comprehensive evaluation structure with seven sustainability dimensions and 35 subcriteria. Third, it provides validated, actionable insights for tropical fruit supply chains in Indonesia. Overall, the integration of these techniques significantly enhances decision reliability and applicability.

RESEARCH METHOD

This study uses a hybrid multi-criteria decision-making (MCDM) approach that integrates the α -cut-based Fuzzy Best–Worst Method (F-BWM α -cut) with Interval-Valued Intuitionistic Fuzzy MABAC (IVIF-MABAC). The selection of this method is based on the need to overcome the limitations of conventional methods, such as AHP or Delphi, which tend to produce high comparison loads, are prone to inconsistency, and are less effective in dealing with linguistic uncertainty [8], [17].

By utilizing the F-BWM α -cut, criterion weights are derived consistently by converting linguistic preferences into numerical intervals. Concurrently, IVIF-MABAC provides a comprehensive ranking of supplier alternatives by simultaneously accommodating degrees of membership, non-membership, and expert uncertainty [15], [16]. To ensure the reliability of the framework, this study includes a sensitivity analysis that confirms model robustness and stakeholder feedback to validate practical relevance. Furthermore, cross-validation using alternative MCDM methods is recommended for future research to enhance external validity.

The Proposed Integrated Fuzzy BWM with α -cut and IVIF-MABAC

This study proposes an integrative framework that combines the α -cut-based Fuzzy Best–Worst Method (F-BWM α -cut) with Interval-Valued Intuitionistic Fuzzy MABAC (IVIF-MABAC). This framework was developed through four stages, all of which began with a literature review to determine

the conceptual basis, then reinforced with expert validation, as illustrated in Figure 1, which depicts the four-stage proposed framework: (1) literature review for criteria identification, (2) criteria weighting using F-BWM α -cut, (3) supplier evaluation using IVIF-MABAC, and (4) final ranking of green supplier alternatives.

Initially, sustainable supplier criteria encompassing economic, social, and environmental dimensions were established from literature [3], [2] and validated via expert focus group discussions (FGDs). To mitigate group-driven biases such as conformity pressure or dominant voices, specific facilitation procedures were employed: Stage 2 weightings were conducted through anonymous individual questionnaires to ensure independent judgment, while Stages 3 and 4 utilized structured turn-taking and neutral moderation to maintain balanced participation and procedural fairness.

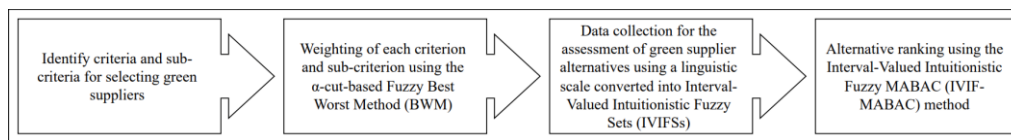


Figure 1. Proposed method for selecting green suppliers

In the second stage, criterion weights were derived using the F-BWM α -cut method. To minimize cognitive load, a linguistic scale was employed, allowing experts to express preferences more naturally than through numerical scales [14]. These qualitative assessments were transformed into Triangular Fuzzy Numbers (TFNs) and processed via α -cuts across three intervals to accommodate uncertainty and ensure weight stability [13]. This multi-interval approach effectively captures varying confidence levels, maintaining a rigorous correlation between linguistic inputs and numerical outputs to enhance the accuracy

of weight estimation within uncertain decision environments.

The justification for choosing this method over AHP is that AHP requires many pairwise comparisons, which increases the potential for inconsistency [17], , while Delphi is more useful for reaching consensus rather than producing consistent weights. Thus, F-BWM α -cut is more suitable for producing efficient, consistent, and adaptive weighting for linguistic uncertainty [18], [19].

During the third and fourth stages, supplier alternatives were evaluated using Interval-Valued Intuitionistic Fuzzy Sets (IVIFSs) and ranked via the IVIF-MABAC method. The application of IVIFSs provides a nuanced assessment by simultaneously incorporating membership, non-membership, and expert hesitancy [16]. Ranking was subsequently established by calculating the closeness coefficient of each alternative relative to the Border Approximation Area (BAA); this approach was selected for its robustness against criteria weight fluctuations and its superior ability to handle interval uncertainty compared to traditional models such as TOPSIS or VIKOR [15].

Although built on existing methods, this study introduces incremental novelty by integrating α -cut-based F-BWM with IVIF-MABAC to evaluate the Indonesian tropical fruit supply chain. This framework handles linguistic ambiguity, improves weight stability, and accounts for expert uncertainty. Furthermore, by employing a comprehensive evaluation scope of seven dimensions and 35 subcriteria, it provides significant theoretical and practical value to a critical sustainability sector.

Evaluation of the Weight of Criteria and Subcriteria in Selecting Green Supplier

The tropical fruit sector faces uncertainty in green supplier evaluation due to seasonal variability, weather-affected quality fluctuations, and inconsistent data among suppliers. In addition, sustainability-related criteria such as traceability, environmental compliance, and social responsibility are subjective and difficult to quantify precisely. These factors cause hesitation and linguistic ambiguity in expert judgments. Therefore, a fuzzy-based approach is appropriate to capture such uncertainties by allowing experts to express preferences linguistically, reflecting real-world vagueness more accurately.

In this section, weighting is applied to the criteria and subcriteria that have been selected for the selection of green suppliers. The weighting is carried out using the α -cut-based Fuzzy Best Worst Method (F-BWM) [20]. The Best Worst Method (BWM) provides an effective approach to handling uncertainty and ambiguity in decision-makers' preferences, which often arise in subjective assessments [14]. The main difference between BWM and Fuzzy BWM α -cut lies in the use of triangular fuzzy numbers that linguistically represent the experts' preferences. These linguistic values are then converted into numerical intervals using the α -cut technique [13]. This approach allows for more accurate weighting results in depicting the existing preference uncertainty.

This method ensures an accurate weighting process by leveraging the Fuzzy BWM α -cut approach to handle the uncertainty and complexity of subjective criteria. It allows decision-makers to express preferences linguistically, which are subsequently converted into consistent, stable numerical weights. The α -cut integration further enhances accuracy by transforming fuzzy numbers into crisp intervals for mathematical computation. Consequently, this methodology provides a robust foundation for in-depth weighting analysis to support strategic, optimal green supplier selection.

$\min \xi$	(1)
$[w_B - w'_j] \leq \xi, \forall_j$	(2)
$[w_j - w''_j] \leq \xi, \forall_j$	(3)
$(l_{Bj} + (m_{Bj} - l_{Bj})\alpha)w_j \leq w'_j$ $\leq (u_{Bj} + (u_{Bj} - m_{Bj})\alpha)w_j, \forall_j$	(4)
$(l_{jw} + (m_{jw} - l_{jw})\alpha)w_w \leq w'_j$ $\leq (u_{jw} + (u_{jw} - m_{jw})\alpha)w_j$	(5)
$\sum_1 w_j = 1$	(6)
$w_j \geq 0$	(7)

$$CR = \frac{\xi^*}{CI} \tag{8}$$

The Fuzzy Best Worst Method (F-BWM) was developed to determine criteria weights more consistently based on expert opinions. The process begins by selecting a set of criteria $\{C_1, C_2, \dots, C_n\}$ which influences a decision. From these criteria, the criteria considered most important (best) (w_B) and least important (worst) (w_W) were determined. These two criteria serve as a reference for comparison with other criteria using a triangular fuzzy number scale, as shown in [Table 1](#).

A fuzzy optimization model was developed to derive optimal weights by minimizing the maximum deviation (ξ) representing the inconsistency between actual and preference-derived weights (Eq. 1). To ensure consistency, the model incorporates constraints bounding the deviation between the weight of the best criterion and other criteria (Eq. 2), as well as between other criteria and the worst criterion (Eq. 3). The model constrains preference values within (α) intervals (Eqs. 4–5) while enforcing sum-to-one (Eq. 6) and

non-negativity (Eq. 7) requirements. Weight reliability is verified through the Consistency Ratio (CR), derived from the optimal deviation (ξ^*) and Consistency Index (CI) (Eq. 8). A result of ($CR \leq 0,1$), signifies that the derived weights are consistent and dependable.

These priority weights inform the subsequent IVIF-MABAC alternative evaluation. This hybrid integration ensures that the weighting phase effectively accounts for uncertainty while the ranking phase provides robust decision outcomes.

Identification of Potential Green Suppliers and Evaluation of Their Performance Based on Sustainability Dimensions

Supplier alternatives were identified through expert collaboration based on production scale, environmental compliance, and logistics capability. Following an FGD-based evaluation using linguistic variables, these assessments were converted into triangular fuzzy numbers (TFNs). The Fuzzy BWM α -cut method was then applied to derive the weights for criteria and sub-criteria, as presented in [Table 1](#).

Table 1. Variable Linguistic and Triangular Fuzzy Number

Linguistic Terms	TFN	Explanation
Equally Important (EI)	(1, 1, 1)	Both elements are equally important
Weakly Important (WI)	(1, 2, 3)	One is slightly more important than the other
Moderate Importance (MI)	(2, 3, 4)	Moderately more important
Moderate Plus Importance (MP)	(3, 4, 5)	Slightly more than moderate importance
Strong Importance (SI)	(4, 5, 6)	Significantly more important
Strong Plus Importance (SP)	(5, 6, 7)	Much more important
Very Strong Importance (VS)	(6, 7, 8)	Almost dominant
Extreme Importance (EX)	(7, 8, 9)	Absolutely dominant

[Table 1](#) presents the linguistic scale and corresponding Triangular Fuzzy Numbers (TFNs) used by experts to express pairwise preference comparisons, ranging from Equally Important (EI) at (1,1,1) to Extreme

Importance (EX) at (7,8,9). These assessments were processed using the α -cut approach to derive criterion and sub-criterion weights [20]. To ensure compatibility with the subsequent IVIF-

MABAC evaluation, each TFN (l, m, u) was mapped to an Interval-Valued Intuitionistic Fuzzy Number (IVIFN) by setting the membership interval to $[l, m]$ and the non-membership interval to $[1-u, 1-m]$, with the remaining uncertainty defining the hesitation degree, thereby preserving semantic integrity and guaranteeing mathematical consistency across the hybrid framework.

Alternative supplier ranking using the IVIF-MABAC method

The final stage involves ranking green supplier alternatives using the IVIF-MABAC method, chosen for its capacity to model uncertainty and expert hesitation through Interval-Valued Intuitionistic Fuzzy Numbers (IVIFNs) [9], [16], [21]. This phase integrates the global weights derived from the F-BWM α -cut, ensuring methodological compatibility between the preference structure and the assessment mechanism. The specific ranking procedures, leveraging these weighted IVIFNs, are outlined below:

$$x_{ijk} = ([a_{ijk}^L, b_{ijk}^U], [c_{ijk}^L, d_{ijk}^U]) \tag{1}$$

Banefit Criteria :

$$n_{ij} = \frac{x_{ij} - x_i^{min}}{x_i^{max} - x_i^{min}} \tag{2}$$

Cost Criteria :

$$n_{ij} = \frac{x_i^{max} - x_{ij}}{x_i^{max} - x_i^{min}}$$

$$r_{ij} = w_j \otimes x_{ij} = ([1 - (1 - a_{ij}^L)^{w_j}, 1 - (1 - b_{ij}^U)^{w_j}], [(c_{ij}^L)^{w_j}, (d_{ij}^U)^{w_j}]) \tag{3}$$

$$\tilde{g}_j = \prod_{i=1}^m (\tilde{r}_{ij})^{\frac{1}{m}} = ([a_{ij}^L, b_{ij}^U], [c_{ij}^L, d_{ij}^U]) \tag{4}$$

$$d_{ij} = \begin{cases} +D_E(\tilde{r}_{ij}, \tilde{g}_j), & \text{if } \tilde{r}_{ij} \geq \tilde{g}_j \\ -D_E(\tilde{r}_{ij}, \tilde{g}_j), & \text{if } \tilde{r}_{ij} \leq \tilde{g}_j \end{cases} \tag{5}$$

$$d_E(\tilde{r}_{ij}, \tilde{g}_j) = \sqrt{\frac{1}{4} (a'_{ij} - a'_j)^2 + (b'_{ij} - b'_j)^2 + (c'_{ij} - c'_j)^2 + (d'_{ij} - d'_j)^2} \tag{6}$$

$$CC_i = \sum_{j=1}^n d_{ij} \tag{7}$$

Implementation begins with constructing an initial decision matrix in which expert assessments are represented as Interval-Valued Intuitionistic Fuzzy Numbers (IVIFNs) (Eq. 1), mapped through a nine-level linguistic scale ranging from 'Extremely Irrelevant' to 'Extremely Relevant' [22]. As presented in Table 2, each linguistic category corresponds to specific IVIFN membership and non-membership intervals from $([0.0; 0.1], [0.8; 0.9])$ to $([0.9; 1.0], [0.0; 0.0])$, ensuring a comprehensive and mathematically consistent representation of expert perceptions [23]. A normalization process is then applied to all decision matrix elements (Eq. 2) to standardize scales across criteria with varying benefit and cost characteristics.

Table 2. Variable Linguistic and Equivalent IVIFs Value

Rating	Linguistic Variable	Equivalent IVIFS Value
1	Extremely irrelevant	$([0.0; 0.1], [0.8; 0.9])$
2	Very irrelevant	$([0.2; 0.2], [0.7; 0.7])$
3	Irrelevant	$([0.3; 0.4], [0.5; 0.6])$
4	Slightly irrelevant	$([0.4; 0.5], [0.5; 0.5])$
5	Fairly relevant	$([0.5; 0.5], [0.4; 0.5])$
6	Slightly relevant	$([0.6; 0.7], [0.2; 0.3])$
7	Relevant	$([0.7; 0.8], [0.2; 0.2])$
8	Very relevant	$([0.8; 0.8], [0.1; 0.1])$
9	Extremely relevant	$([0.9; 1.0], [0.0; 0.0])$

Normalized values are integrated with global F-BWM α -cut weights to produce a weighted decision matrix (Eq. 3), ensuring each alternative's contribution is accurately reflected across all sustainability dimensions. Subsequently, the Border Approximation Area (BAA) is established as the ideal reference. Calculated by aggregating weighted values \tilde{r}_{ij} across m alternatives (Eq. 4), the BAA \tilde{g}_j represents the average performance threshold for each criterion.

Post-BAA calculation, the geometric distance d_{ij} between weighted values \tilde{r}_{ij} and the threshold \tilde{g}_j is determined using Euclidean distance for IVIFNs (Eqs. 5–6). A positive d_{ij} denotes performance exceeding the BAA, whereas a negative value indicates a shortfall. These distances are aggregated into a Closeness Coefficient (CC_i) (Eq. 7) to measure proximity to the ideal BAA vector. Alternatives are then ranked, with the highest (CC_i) identifying the optimal supplier. Ultimately, the IVIF-MABAC framework ensures a robust selection process by balancing economic, social, and environmental sustainability under uncertainty.

Data Collection

Criteria weights and alternative evaluations were determined by three domain experts selected via purposive sampling to ensure relevant competencies across the sustainable tropical fruit supply chain: an academic with 20 years in supply chain research, a procurement manager with 15 years in tropical fruit exports and green certification, and a sustainability consultant with 12 years in perishable commodities.

Data collection was structured in two stages. First, an online questionnaire for F-BWM α -cut-based criteria weighting was refined through a pilot test to ensure linguistic clarity and response consistency. Second, a two-hour offline Focus Group Discussion (FGD) was conducted for IVIF-based supplier evaluation, ensuring that multi-dimensional expertise was systematically captured while maintaining methodological rigor across both the weighting and ranking phases.

To ensure reliable aggregation, individual expert judgments were consolidated using the fuzzy geometric mean prior to the α -cut transformation, enabling proportional integration of each expert's linguistic preferences. Consistency Ratios (CR) calculated for each criterion and sub-criterion group based on the F-BWM formulation [20] all yielded values below 0.10, confirming sufficient assessment consistency. Although purposive sampling guarantees domain specificity, potential selection bias and limited regional representation are acknowledged as limitations, and future research should engage a more diverse expert panel to strengthen generalizability.

During the criteria evaluation stage, experts expressed their preferences using a linguistic scale that was subsequently converted into Triangular Fuzzy Numbers (TFNs). Table 3 presents the best and worst criteria identified by each decision-maker (DM), from which pairwise comparisons using the F-BWM formulation were conducted to derive relative criterion weights and establish a final ranked hierarchy for green supplier evaluation.

Table 3. Priorities of the criteria determined by the experts

Criteria	E	T	P	S	L	Q	O
DM1 (B/W)	EI/MI	SI/SP	EX/EI	VS/MP	WI/MI	VS/EX	MI/SP

Criteria	E	T	P	S	L	Q	O
DM2 (B/W)	MP/MP	EX/EI	SP/SP	EI/EX	MI/MI	VS/WI	MP/EX
DM3 (B/W)	SP/MP	MP/MI	MP/MP	SI/SP	EX/EI	EI/EX	SP/SI

The same process was subsequently applied at the sub-criteria level, where experts evaluated sub-criteria under each main criterion using a linguistic scale converted into TFNs. The best and worst sub-criteria within each group were identified for pairwise comparison, yielding

priority weights that, when combined with the main criteria weights, provide a comprehensive picture of the overall priority structure in decision-making. The complete linguistic preference assessments at the sub-criteria level for all three decision makers are summarized in [Table 4](#).

Table 4. Priorities of the sub-criteria determined by the experts

Criteria (E)	E1	E2	E3	E4	E5
DM1 (B/W)	EI/E3	MI/EX	EX/EI	MP/MP	SP/MI
DM2 (B/W)	MP/MP	EX/EI	SP/SP	EI/EX	MI/MI
DM3 (B/W)	E1/E5	MP/MI	MP/MP	SI/SP	EX/EI
Criteria (T)	T1	T2	T3	T4	T5
DM1 (B/W)	EI/T2	MI/EI	SP/SI	SP/SP	MP/EX
DM2 (B/W)	MP/T2	VS/EI	WI/MP	EI/MI	MP/MI
DM3 (B/W)	SP/T1	WI/MP	EI/SI	EX/EI	MP/SP
Criteria (P)	P1	P2	P3	P4	P5
DM1 (B/W)	MP/WI	SI/EI	EX/VS	EI/WI	SP/MP
DM2 (B/W)	EX/EX	EI/SP	SI/EI	MP/MI	WI/WI
DM3 (B/W)	EI/WI	MP/EX	MI/MP	SP/SI	VS/EI
Criteria (S)	S1	S2	S3	S4	S5
DM1 (B/W)	EX/WI	SP/WI	EI/VS	MI/EI	VS/SP
DM2 (B/W)	MP/E1	EI/EX	VS/MP	EX/SP	VS/MI
DM3 (B/W)	SI/VS	VS/E1	VS/VS	EI/EX	VS/SP
Criteria (L)	L1	L2	L3	L4	L5
DM1 (B/W)	EI/MI	MP/EX	EX/EI	WI/WI	MP/SP
DM2 (B/W)	WI/VS	EI/SP	MP/EI	SP/WI	SI/SI
DM3 (B/W)	MP/SP	MP/MI	WI/EI	SP/VS	EI/EX
Criteria (Q)	Q1	Q2	Q3	Q4	Q5
DM1 (B/W)	VS/EX	SI/EI	E1/MP	MI/SI	EX/SP
DM2 (B/W)	MP/SI	EI/EX	SP/EX	EX/E1	MP/WI
DM3 (B/W)	VS/EX	MI/SI	EI/SP	SI/EI	SI/MP
Criteria (O)	O1	O2	O3	O4	O5
DM1 (B/W)	WI/VS	EI/MI	MP/EI	SP/WI	MP/SI
DM2 (B/W)	MP/SP	MP/MI	WI/EI	SP/VS	EI/WI
DM3 (B/W)	MP/EI	WI/SP	MP/SI	EI/EI	EX/SI

[Table 5](#) presents the IVIF decision matrix reflecting expert assessments of ten green

supplier alternatives across 35 subcriteria, where each evaluation is expressed as an

Interval-Valued Intuitionistic Fuzzy Number (IVIFN) to capture membership, non-membership, and hesitation degrees under uncertainty.

Table 5. IVIF decision matrix

Code	Type	1 st GS	2 nd GS	...	9 th GS	10 th GS
E1	Cost	([0.6,0.7],[0.2,0.3])	([0.3,0.4],[0.5,0.6])	....	([0.6,0.7],[0.2,0.3])	([0.6,0.7],[0.2,0.3])
E2	Cost	([0.4,0.5],[0.5,0.5])	([0.7,0.8],[0.2,0.2])	....	([0.8,0.8],[0.1,0.1])	([0.4,0.5],[0.5,0.5])
E3	Benefit	([0.2,0.2],[0.7,0.7])	([0.7,0.8],[0.2,0.2])	....	([0.6,0.7],[0.2,0.3])	([0.2,0.2],[0.7,0.7])
E4	Benefit	([0.2,0.2],[0.7,0.7])	([0.2,0.2],[0.7,0.7])	....	([0.4,0.5],[0.5,0.5])	([0.2,0.2],[0.7,0.7])
E5	Cost	([0.6,0.7],[0.2,0.3])	([0.4,0.5],[0.5,0.5])	....	([0.4,0.5],[0.5,0.5])	([0.6,0.7],[0.2,0.3])
T1	Benefit	([0.8,0.8],[0.1,0.1])	([0.6,0.7],[0.2,0.3])	....	([0.7,0.8],[0.2,0.2])	([0.8,0.8],[0.1,0.1])
T2	Cost	([0.7,0.8],[0.2,0.2])	([0.2,0.2],[0.7,0.7])	....	([0.2,0.2],[0.7,0.7])	([0.7,0.8],[0.2,0.2])
T3	Benefit	([0.5,0.5],[0.4,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.7,0.8],[0.2,0.2])	([0.5,0.5],[0.4,0.5])
T4	Benefit	([0.6,0.7],[0.2,0.3])	([0.6,0.7],[0.2,0.3])	....	([0.2,0.2],[0.7,0.7])	([0.6,0.7],[0.2,0.3])
T5	Benefit	([0.2,0.2],[0.7,0.7])	([0.3,0.4],[0.5,0.6])	....	([0.3,0.4],[0.5,0.6])	([0.2,0.2],[0.7,0.7])
P1	Benefit	([0.7,0.8],[0.2,0.2])	([0.6,0.7],[0.2,0.3])	....	([0.2,0.2],[0.7,0.7])	([0.8,0.8],[0.1,0.1])
P2	Benefit	([0.2,0.2],[0.7,0.7])	([0.8,0.8],[0.1,0.1])	....	([0.2,0.2],[0.7,0.7])	([0.6,0.7],[0.2,0.3])
P3	Benefit	([0.4,0.5],[0.5,0.5])	([0.6,0.7],[0.2,0.3])	....	([0.5,0.5],[0.4,0.5])	([0.8,0.8],[0.1,0.1])
P4	Benefit	([0.4,0.5],[0.5,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.7,0.8],[0.2,0.2])	([0.4,0.5],[0.5,0.5])
P5	Benefit	([0.2,0.2],[0.7,0.7])	([0.2,0.2],[0.7,0.7])	....	([0.8,0.8],[0.1,0.1])	([0.8,0.8],[0.1,0.1])
S1	Benefit	([0.4,0.5],[0.5,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.2,0.2],[0.7,0.7])	([0.8,0.8],[0.1,0.1])
S2	Benefit	([0.6,0.7],[0.2,0.3])	([0.6,0.7],[0.2,0.3])	....	([0.7,0.8],[0.2,0.2])	([0.6,0.7],[0.2,0.3])
S3	Benefit	([0.6,0.7],[0.2,0.3])	([0.7,0.8],[0.2,0.2])	....	([0.8,0.8],[0.1,0.1])	([0.6,0.7],[0.2,0.3])
S4	Benefit	([0.5,0.5],[0.4,0.5])	([0.6,0.7],[0.2,0.3])	....	([0.3,0.4],[0.5,0.6])	([0.6,0.7],[0.2,0.3])
S5	Benefit	([0.2,0.2],[0.7,0.7])	([0.2,0.2],[0.7,0.7])	....	([0.3,0.4],[0.5,0.6])	([0.8,0.8],[0.1,0.1])
L1	Benefit	([0.4,0.5],[0.5,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.4,0.5],[0.5,0.5])	([0.2,0.2],[0.7,0.7])
L2	Benefit	([0.3,0.4],[0.5,0.6])	([0.3,0.4],[0.5,0.6])	....	([0.8,0.8],[0.1,0.1])	([0.4,0.5],[0.5,0.5])
L3	Benefit	([0.4,0.5],[0.5,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.7,0.8],[0.2,0.2])	([0.3,0.4],[0.5,0.6])
L4	Cost	([0.4,0.5],[0.5,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.6,0.7],[0.2,0.3])	([0.4,0.5],[0.5,0.5])
L5	Benefit	([0.7,0.8],[0.2,0.2])	([0.3,0.4],[0.5,0.6])	....	([0.6,0.7],[0.2,0.3])	([0.4,0.5],[0.5,0.5])
Q1	Benefit	([0.2,0.2],[0.7,0.7])	([0.7,0.8],[0.2,0.2])	....	([0.8,0.8],[0.1,0.1])	([0.7,0.8],[0.2,0.2])
Q2	Cost	([0.4,0.5],[0.5,0.5])	([0.7,0.8],[0.2,0.2])	....	([0.6,0.7],[0.2,0.3])	([0.2,0.2],[0.7,0.7])
Q3	Benefit	([0.2,0.2],[0.7,0.7])	([0.2,0.2],[0.7,0.7])	....	([0.7,0.8],[0.2,0.2])	([0.2,0.2],[0.7,0.7])
Q4	Benefit	([0.4,0.5],[0.5,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.3,0.4],[0.5,0.6])	([0.3,0.4],[0.5,0.6])
Q5	Benefit	([0.2,0.2],[0.7,0.7])	([0.8,0.8],[0.1,0.1])	....	([0.6,0.7],[0.2,0.3])	([0.8,0.8],[0.1,0.1])
O1	Benefit	([0.4,0.5],[0.5,0.5])	([0.3,0.4],[0.5,0.6])	....	([0.2,0.2],[0.7,0.7])	([0.2,0.2],[0.7,0.7])
O2	Benefit	([0.3,0.4],[0.5,0.6])	([0.2,0.2],[0.7,0.7])	....	([0.6,0.7],[0.2,0.3])	([0.3,0.4],[0.5,0.6])
O3	Benefit	([0.4,0.5],[0.5,0.5])	([0.4,0.5],[0.5,0.5])	....	([0.8,0.8],[0.1,0.1])	([0.4,0.5],[0.5,0.5])
O4	Benefit	([0.7,0.8],[0.2,0.2])	([0.6,0.7],[0.2,0.3])	....	([0.3,0.4],[0.5,0.6])	([0.7,0.8],[0.2,0.2])
O5	Benefit	([0.5,0.5],[0.4,0.5])	([0.5,0.5],[0.4,0.5])	....	([0.3,0.4],[0.5,0.6])	([0.5,0.5],[0.4,0.5])

Case Application

This research focuses on the selection of sustainable suppliers in the Indonesian tropical agriculture supply chain specifically for avocados, durians, and mangosteens with the active involvement of academic and practitioner experts. The study began with a comprehensive literature review

addressing economic, social, and environmental sustainability dimensions to compile an initial evaluation framework. Following validation through a Focus Group Discussion (FGD), this process established a consensus on seven main criteria and 35 subcriteria relevant to tropical fruit supplier selection, as detailed in [Table 6](#).

Table 6. Criteria and sub-criteria selection of green supplier

Criteria	Subcriteria	Type	Code
Cost and Economic Efficiency	Product Price	Cost	E1
	Transportation Cost	Cost	E2
	Shipping Volume Efficiency	Benefit	E3
	Payment Flexibility	Benefit	E4
	Additional or Hidden Costs	Cost	E5
Delivery Timeliness & Reliability	Delivery Timeliness	Benefit	T1
	Lead Time	Cost	T2
	Cold Chain Reliability	Benefit	T3
	Order Fulfillment Rate	Benefit	T4
	Responsiveness to Sudden Demand	Benefit	T5
Eco-Friendly & Innovative Agriculture	Organic Fertilizer & Pesticides	Benefit	P1
	Water-Saving Irrigation	Benefit	P2
	Agroforestry System	Benefit	P3
	Adaptation to Climate Change	Benefit	P4
	Green Technology (IoT, sensors)	Benefit	P5
Collaborative & Responsive Capability	Communication & Coordination	Benefit	S1
	Complaint Handling	Benefit	S2
	Partnership Commitment	Benefit	S3
	Contract Clarity	Benefit	S4
	Response Speed	Benefit	S5
Environmental Competency	Environmental Certification (ISO, Organic)	Benefit	L1
	Waste Management	Benefit	L2
	Clean Energy Usage	Benefit	L3
	Operational Carbon Footprint	Cost	L4
	CSR or Conservation Activities	Benefit	L5
Product Quality	Product Qualification Rate	Benefit	Q1
	Reject Rate	Cost	Q2
	Conformity to Fruit Grading Standards	Benefit	Q3
	Quality Consistency	Benefit	Q4
	Pesticide Residue-Free	Benefit	Q5
	Digital Traceability System	Benefit	O1
	Batch Code & Planting Location	Benefit	O2

Product	Input Information (fertilizer/pesticide)	Benefit	O3
Transparency & Traceability	Buyer Data Access	Benefit	O4
	Production Audit Transparency	Benefit	O5

Table 6 presents the complete framework of seven main criteria and 35 subcriteria, spanning Cost and Economic Efficiency (E), Delivery Timeliness and Reliability (T), Eco-Friendly and Innovative Agriculture (P), Collaborative and Responsive Capability (S), Environmental Competency (L), Product Quality (Q), and Product Transparency and Traceability (O). Validated through expert FGDs and literature cross-checks to address potential conceptual overlap. Each subcriterion is classified as benefit or cost type to guide the evaluation. Supplier alternatives were then characterized and assessed using a fuzzy linguistic scale, with responses mapped to TFNs to establish a fuzzy score matrix. Ultimately, F-BWM α -cut weights were integrated into the IVIF-MABAC framework to derive proximity coefficients, ensuring robust alternative ranking under conditions of uncertainty;

future research should employ statistical dimensionality analysis to further refine these components.

Determine the criteria and subcriteria

The global weights of all criteria and subcriteria derived from the F-BWM α -cut procedure are presented in Table 7, reflecting the relative significance of each component in the strategic selection of green suppliers. The results show that Product Quality (Q) and Product Transparency and Traceability (O) carry the highest dimension weights, with Conformity to Fruit Grading Standards (Q3) and Production Audit Transparency (O5) ranking among the top-weighted subcriteria, underscoring their critical role in sustainable supplier evaluation within the tropical fruit supply chain.

Table 7. Weight of Criteria and Subcriteria for Selecting Green Suppliers

Criteria	Subcriteria	Local Weight	Dimension Weight	Global Weight	Rank
Cost and Economic Efficiency	Product Price	0,1528		0,0181	34
	Transportation Cost	0,1544		0,0182	33
	Shipping Volume Efficiency	0,2343	0,1181	0,0277	19
	Payment Flexibility	0,2412		0,0285	16
	Additional or Hidden Costs	0,2173		0,0257	23
Delivery Timeliness & Reliability	Delivery Timeliness	0,1625		0,0224	27
	Lead Time	0,1543		0,0213	30
	Cold Chain Reliability	0,2066	0,1379	0,0285	17
	Order Fulfillment Rate	0,2093		0,0289	14
	Responsiveness to Sudden Demand	0,2673		0,0369	6
Eco-Friendly & Innovative Agriculture	Organic Fertilizer & Pesticides	0,3288		0,0490	1
	Water-Saving Irrigation	0,1481	0,1491	0,0221	29
	Agroforestry System	0,1794		0,0268	20
	Adaptation to Climate Change	0,1481		0,0221	28

Criteria	Subcriteria	Local Weight	Dimension Weight	Global Weight	Rank
	Green Technology (IoT, sensors)	0,1956		0,0292	13
Collaborative & Responsive Capability	Communication & Coordination	0,1699	0,1451	0,0246	26
	Complaint Handling	0,1390		0,0202	32
	Partnership Commitment	0,2209		0,0321	10
	Contract Clarity	0,2017		0,0293	12
	Response Speed	0,2685		0,0390	5
Environmental Competency	Environmental Certification (ISO, Organic)	0,2241	0,1128	0,0253	25
	Waste Management	0,1858		0,0210	31
	Clean Energy Usage	0,1319		0,0149	35
	Operational Carbon Footprint	0,2246		0,0253	24
	CSR or Conservation Activities	0,2336		0,0263	21
Product Quality	Product Qualification Rate	0,2297	0,1733	0,0398	4
	Reject Rate	0,1644		0,0285	15
	Conformity to Fruit Grading Standards	0,2425		0,0420	2
	Quality Consistency	0,1913		0,0332	8
	Pesticide Residue-Free	0,1721		0,0298	11
Product Transparency & Traceability	Digital Traceability System	0,2146	0,1637	0,0351	7
	Batch Code & Planting Location	0,1597		0,0261	22
	Input Information (fertilizer/pesticide)	0,1723		0,0282	18
	Buyer Data Access	0,2013		0,0329	9
	Production Audit Transparency	0,2520		0,0412	3

This study identifies product quality as the primary criterion in tropical fruit supplier selection, echoing MCDM research that prioritizes consistency due to food safety risks and limited shelf lives [4], [24] and [18]. While cost and flexibility often dominate in non-perishable manufacturing, our results confirm that perishability and safety regulations fundamentally moderate supplier priorities. Ultimately, this underscores quality as the critical determinant for sustainability and performance within the tropical fruit supply

chain. The emphasis on traceability and transparency aligns with research on Indonesian tropical fruit exports, where e-traceability and blockchain are essential for quality assurance and consumer trust [5] and [25]. While domestic food systems may prioritize cost optimization, the importance of traceability is amplified in high-risk export sectors due to the necessity of compliance, recall management, and reputation protection. This underscores traceability as a critical determinant of

supplier credibility within perishable, export-oriented supply chains.

Our findings indicate that delivery timeliness and logistics reliability are critical for top supplier rankings, aligning with literature that identifies cold-chain performance as a pillar of agri-fresh sustainability. While static manufacturing sectors often prioritize cost optimization, our results demonstrate that on-time delivery in agribusiness directly reduces post-harvest losses and enhances environmental efficiency. Ultimately, this confirms that the inherent perishability of tropical fruits necessitates the dominance of logistical performance within green supplier evaluation frameworks.

Unlike manufacturing-based studies prioritizing cost and our research identifies cost as a secondary factor in green supplier selection for tropical fruits. Consistent with agrifood literature, these findings suggest that minor price advantages cannot compensate for deficiencies in traceability or quality. Ultimately, the high risk of shipment rejection ensures that quality and traceability imperatives overshadow cost

efficiency within perishable agri-food markets.

Environmental and social dimensions demonstrate moderate importance, supporting the Triple Bottom Line (TBL) framework by balancing economic, ecological, and social objectives. While eco-packaging and fair labor practices foster collaboration, their weighting in Indonesia remains lower than in strictly regulated markets due to inconsistent enforcement. Consequently, these results validate TBL relevance while highlighting the necessity for stronger institutional incentives to elevate sustainability criteria in developing economies by [25].

The consistency of expert judgments was verified using the Consistency Ratio (CR) for each criterion and sub-criterion group based on the F-BWM formulation [20], as presented in Table 8. A CR value below 0.10, which is widely recognized in F-BWM applications as a reasonable limit of consistency, confirms that the derived weights are reliable for further analysis. If this threshold is exceeded, expert preferences are re-evaluated to maintain reliability.

Table 8. Consistency Ratio

CR						
Q	T	E	S	L	P	O
0,062624816	0,07846641	0,0856821	0,08264066	0,0853904	0,08065094	0,06890899

As detailed in Table 8, all CR values in this study fall below the 0.10 threshold, ranging from 0.062 (Q) to 0.086 (E), confirming sufficient consistency of expert assessments across all criterion groups.

Determine of final solution using the MABAC method

To apply this method, linguistic evaluations were transformed into interval-valued intuitionistic fuzzy numbers (IVIF) to

capture hesitation and interval uncertainty. The IVIF values were then weighted using an α -cut-based Fuzzy Best-Worst Method (FBWM), which reduces information loss from triangular fuzzy judgments and provides a consistency index/ratio for the derived weights [20].

The “ideal boundary area” in MABAC represents the optimal condition, alternatives relative distances to this

boundary yield a closeness/score coefficient (CC_i) that expresses preference higher (CC_i) indicates a better option. Recent MABAC variants under richer fuzzy environments (e.g., hesitant/IVIF) formalize this distance-to-boundary scoring and show stable rankings in uncertain MAGDM contexts.

Empirical studies applying IVIF-MABAC-type frameworks in complex evaluations (e.g., cold-chain risk, teaching-quality/material selection) further demonstrate robustness and consistent ordering under ambiguity. Accordingly, the green supplier with the highest CC_i is selected as most suitable, and the final ranking is reported in [Table 9](#), which shows that the 4th Green Supplier achieved the highest CC_i score (0.925), followed by the 1st Green Supplier (0.922) and 9th Green

Supplier (0.913), while the 8th Green Supplier ranked lowest (0.724).

From a methodological perspective, the robustness of rankings across weighting scenarios is consistent with prior IVIF-MABAC studies in agriculture and logistics, which demonstrate stable ordering despite differences in expert judgment and data uncertainty. Our use of α -cut-based F-BWM further reduces inconsistency by integrating hesitation into fuzzy pairwise comparisons, supporting the methodological soundness of the hybrid approach. Nonetheless, differences in linguistic scale or aggregation rules across other studies may yield minor rank variations, emphasizing the need for harmonized evaluation frameworks in future comparative analyses.

Table 9. Ranking of Green Suppliers

Code	CC_i									
	1 st GS	2 nd GS	3 rd GS	4 th GS	5 th GS	6 th GS	7 th GS	8 th GS	9 th GS	10 th GS
E1	0,007	0,029	0,007	0,019	0,019	0,019	0,006	0,006	0,006	0,006
E2	0,018	0,016	0,016	0,017	0,016	0,017	0,008	0,011	0,031	0,013
E3	0,034	0,034	0,008	0,055	0,008	0,021	0,017	0,013	0,021	0,029
E4	0,029	0,024	0,064	0,011	0,009	0,028	0,028	0,005	0,009	0,024
E5	0,022	0,007	0,011	0,024	0,011	0,003	0,023	0,003	0,007	0,024
T1	0,043	0,012	0,020	0,012	0,020	0,049	0,012	0,012	0,011	0,020
T2	0,029	0,023	0,016	0,008	0,011	0,014	0,042	0,014	0,023	0,026
T3	0,021	0,020	0,037	0,037	0,050	0,025	0,050	0,050	0,029	0,016
T4	0,017	0,018	0,021	0,021	0,054	0,012	0,017	0,018	0,034	0,018
T5	0,033	0,011	0,007	0,056	0,056	0,027	0,039	0,011	0,011	0,027
P1	0,058	0,030	0,029	0,022	0,052	0,038	0,030	0,059	0,059	0,087
P2	0,027	0,046	0,013	0,046	0,023	0,013	0,018	0,011	0,023	0,018
P3	0,023	0,016	0,033	0,016	0,021	0,012	0,049	0,016	0,012	0,049
P4	0,013	0,007	0,007	0,020	0,020	0,020	0,011	0,048	0,030	0,007
P5	0,039	0,034	0,034	0,021	0,020	0,020	0,013	0,020	0,056	0,056
S1	0,020	0,014	0,014	0,010	0,046	0,010	0,010	0,027	0,029	0,046
S2	0,005	0,004	0,024	0,030	0,020	0,014	0,004	0,016	0,014	0,004
S3	0,021	0,036	0,020	0,039	0,039	0,039	0,059	0,020	0,059	0,021
S4	0,028	0,008	0,021	0,021	0,043	0,043	0,033	0,028	0,033	0,008
S5	0,059	0,053	0,065	0,037	0,019	0,019	0,019	0,029	0,036	0,065

Code	Cci									
	1 st GS	2 nd GS	3 rd GS	4 th GS	5 th GS	6 th GS	7 th GS	8 th GS	9 th GS	10 th GS
L1	0,009	0,002	0,002	0,002	0,039	0,002	0,002	0,002	0,002	0,018
L2	0,020	0,015	0,023	0,015	0,008	0,013	0,015	0,023	0,040	0,012
L3	0,010	0,006	0,015	0,031	0,015	0,012	0,006	0,012	0,019	0,009
L4	0,012	0,006	0,025	0,006	0,021	0,021	0,006	0,036	0,025	0,006
L5	0,014	0,041	0,011	0,029	0,029	0,029	0,008	0,008	0,008	0,035
Q1	0,063	0,034	0,034	0,039	0,034	0,039	0,016	0,025	0,064	0,034
Q2	0,021	0,032	0,010	0,055	0,010	0,019	0,020	0,015	0,019	0,033
Q3	0,048	0,040	0,086	0,022	0,017	0,035	0,035	0,011	0,055	0,040
Q4	0,010	0,006	0,019	0,055	0,004	0,004	0,004	0,004	0,004	0,004
Q5	0,052	0,045	0,028	0,046	0,024	0,024	0,024	0,045	0,011	0,045
O1	0,012	0,005	0,042	0,007	0,020	0,005	0,007	0,042	0,020	0,020
O2	0,023	0,028	0,052	0,012	0,032	0,019	0,008	0,017	0,019	0,017
O3	0,029	0,022	0,025	0,040	0,025	0,046	0,025	0,027	0,046	0,022
O4	0,037	0,017	0,016	0,021	0,017	0,021	0,032	0,028	0,028	0,032
O5	0,014	0,006	0,053	0,020	0,006	0,013	0,053	0,013	0,020	0,006
Σ	0,922	0,747	0,910	0,925	0,858	0,744	0,748	0,724	0,913	0,896
Rank	2	8	4	1	6	9	7	10	3	5

Sensitivity Analysis

Sensitivity analysis was conducted by modifying the weights of criteria and sub-criteria across five different scenarios to examine their impact on supplier ranking outcomes. The recalculation results using the IVIF-MABAC method show that 4th Green Supplier consistently ranks at the top in almost all scenarios, indicating the stability and robustness of its performance under varying priority structures [16], [22]. The IVIF-MABAC framework operates on several theoretical assumptions, primarily that Interval-Valued Intuistic Fuzzy Sets (IVIFSs) effectively capture expert hesitation and that proximity distance calculations remain stable across varying interval widths [21]. Furthermore, outcomes are inherently influenced by the calibration of linguistic scales and the specific construction of membership and non-membership intervals. These methodological dependencies necessitate a cautious interpretation of sensitivity outcomes, particularly within high-

uncertainty environments like tropical fruit supply chains where subjective judgment significantly shapes sustainability evaluations [1], [2], [3].

While the 4th Green Supplier demonstrates consistent performance, the sensitivity analysis highlights distinct strategic strengths among other alternatives. The 1st Green Supplier maintains stability through a balanced capability profile, whereas the 9th Green Supplier excels in scenarios emphasizing collaboration and innovation. These findings suggest that the optimal choice may shift according to specific organizational priorities-such as partnership potential or environmental leadership-rather than relying solely on aggregate rankings [8], [20].

Beyond ordinal rankings, the magnitude of score differences was examined to prevent the misinterpretation of performance gaps. For instance, the narrow margin between the 4th Green Supplier (C*Ci* = 0.925) and the 1st Green Supplier (C*Ci* = 0.922) suggests

nearly equivalent performance despite their distinct ranks. These minimal gaps underscore the necessity of evaluating both ranking order and numerical distances to achieve a more nuanced and accurate assessment of supplier performance [9].

The sensitivity analysis utilizes five strategic scenarios to simulate realistic procurement shifts: economic-oriented (Scenario 1), social compliance (Scenario 2),

environmental sustainability (Scenario 3), collaboration-driven (Scenario 4), and a balanced holistic perspective (Scenario 5). Collectively, these scenarios illustrate how supplier rankings fluctuate under varying strategic priorities, offering managers critical insights into system stability and contextual decision-making. The CCI scores and ranking variations across all green supplier alternatives under the five scenarios are presented in Table 10.

Table 10. Results of the Sensitivity Analysis for Selecting Green Suppliers

Green Supplier	Initial Mode	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1 st Green Supplier	0,922	0,886	0,901	0,871	0,927	0,919
2 nd Green Supplier	0,747	0,765	0,762	0,767	0,798	0,750
3 rd Green Supplier	0,910	0,882	0,898	0,866	0,950	0,865
4 th Green Supplier	0,925	0,981	0,919	0,938	0,933	0,965
5 th Green Supplier	0,858	0,870	0,858	0,891	0,843	0,907
6 th Green Supplier	0,744	0,755	0,739	0,761	0,784	0,774
7 th Green Supplier	0,748	0,731	0,731	0,727	0,762	0,745
8 th Green Supplier	0,724	0,705	0,747	0,723	0,711	0,776
9 th Green Supplier	0,913	0,876	0,926	0,916	0,914	0,915
10 th Green Supplier	0,896	0,852	0,876	0,870	0,851	0,875

As shown in Table 10, the 4th Green Supplier consistently maintains the highest rank across most scenarios, confirming the robustness of its overall sustainability performance, while the 8th Green Supplier

remains the lowest-ranked. These findings are further illustrated in Figure 2, validating the stability of the proposed hybrid framework across varying strategic priorities.

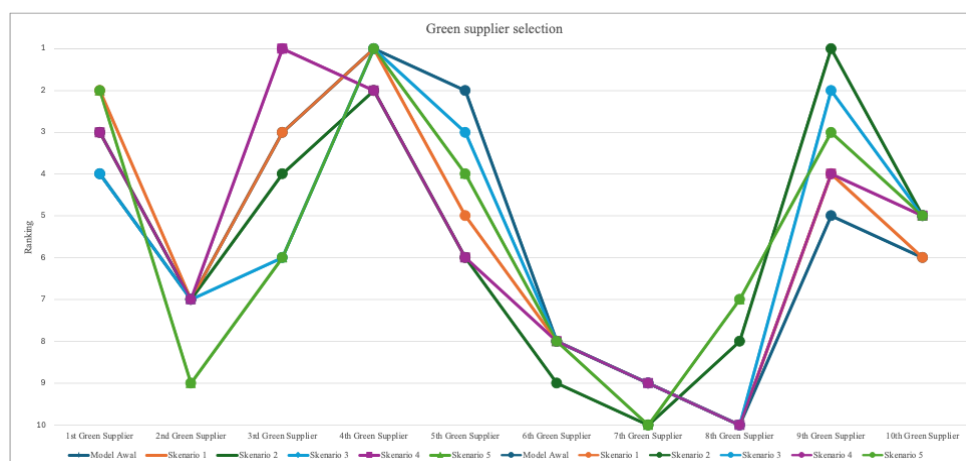


Figure 2. Graph of the Results of the Sensitivity Analysis of Green Supply Selection

Figure 2 confirms the consistent dominance of the 4th Green Supplier across all five scenarios, while the 8th Green Supplier

remains the lowest-ranked, validating the robustness of the proposed hybrid framework.

IMPLICATIONS

This study generates several implications for both theoretical understanding and practical applications in sustainable supplier evaluation.

1. Theoretical understanding

This study contributes to the theoretical discourse on sustainable supplier evaluation by demonstrating that product quality and transparency/traceability are the primary determinants in the tropical fruit sector. These findings diverge from traditional manufacturing literature, which typically prioritizes cost and operational efficiency. By identifying a contextual moderation effect—where perishability, food safety risks, and export compliance reshape the hierarchy of sustainability criteria—this research extends supplier selection theory. Ultimately, it establishes that the inherent attributes of perishable commodities necessitate a theoretical shift from cost-centric models toward frameworks driven by safety, quality, and traceability.

Second, this research refines MCDM theory by elevating traceability—including digital systems, batch-level accuracy, and audit transparency—from a supporting factor to a primary determinant of sustainable performance, highlighting the critical link between supply chain risk exposure and information transparency. Third, the study advances methodological theory through a hybrid framework integrating the F-BWM α -cut and IVIF-MABAC methods, which effectively captures linguistic ambiguity and expert hesitation to ensure stable, robust decision-making in complex environments. Lastly, the established hierarchy of seven dimensions and 35 subcriteria serves as an empirically validated reference structure for future agri-food research, streamlining problem structuring and strengthening the

theoretical foundation for sustainable supplier selection in perishable contexts.

2. Practical Applications

The proposed F-BWM α -cut and IVIF-MABAC framework offers actionable insights for managers, government agencies, certification bodies, and other stakeholders in the tropical fruit supply chain. First, the global weights can be integrated into procurement dashboards to compute sustainability scores and automate supplier ranking using IVIF-MABAC. This transforms the hybrid model into an operational decision-support system that standardizes supplier evaluation under uncertainty.

Managers should prioritize resource allocation toward product quality, audit transparency, and digital traceability, employing phased implementation strategies—ranging from basic digital audits to advanced blockchain or IoT systems—to accommodate infrastructure and literacy constraints. Furthermore, certification bodies and government agencies can leverage the weighted criteria ([Table 7.](#)) to refine audit checklists and design targeted incentives, such as subsidies for eco-friendly practices, to enhance export competitiveness. Finally, by adopting operational mechanisms like mandatory digital logbooks and standardized cold-chain reporting, organizations can translate these criteria into measurable performance indicators, fostering a transparent, data-driven framework for long-term supplier development.

CONCLUSION

This study introduces a hybrid evaluation framework for green supplier selection, integrating the F-BWM α -cut and IVIF-MABAC methods. Findings identify product quality and transparency/traceability as the

most influential criteria, with 4th Green Supplier emerging as the optimal alternative due to its consistent performance across sustainability dimensions. Theoretically, this research advances fuzzy MCDM applications within perishable supply chains by simultaneously addressing linguistic ambiguity and interval hesitation-filling a critical methodological gap left by deterministic and single-type fuzzy approaches. The framework offers robust decision support by prioritizing consistent performance-exemplified by 4th Green Supplier over isolated criterion

excellence (9th Green Supplier), thereby reducing selection bias and operational risk. This ESG-driven approach is scalable to other agrifood and traceability-intensive industries such as pharmaceuticals and cosmetics. Limitations include a small expert panel and geographic focus on Indonesia, which may constrain generalizability to more stringent regulatory environments. Future research should integrate real-time IoT data and validate the framework across broader perishable supply chains to enhance scalability and decision support dynamism.









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