A Hybrid Fuzzy Delphi–AHP–TOPSIS Framework for Green Supplier Selection: A Case Study in the Garment Industry

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**Abstract.** Green supplier selection has become an essential component of sustainable supply chain management, as organizations are increasingly expected to align economic efficiency with environmental responsibility. This study develops a hybrid decision-making framework that integrates fuzzy Delphi, fuzzy Analytic Hierarchy Process (AHP), and fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to enhance supplier evaluation under uncertainty. Fuzzy Delphi was applied to refine and validate relevant criteria, fuzzy AHP was employed to determine criterion weights, and fuzzy TOPSIS was used to rank supplier alternatives. The proposed framework was tested in a garment company. The findings reveal that quality, cost, and delivery are the most critical evaluation criteria, while environmental factors, although less prioritized, remain relevant to sustainable decision-making. The supplier ranking results identified supplier A2 as the most suitable partner. Managerial implications highlight the importance of quality assurance, cost efficiency, and delivery reliability, supported by sustainability practices such as environmental certifications and eco-friendly packaging. The framework provides both theoretical and practical contributions by offering a robust and transparent approach for green supplier selection in uncertain environments.

**Keywords:** Green supplier selection, Fuzzy Delphi, Fuzzy AHP, Fuzzy TOPSIS, Sustainable supply chain

# INTRODUCTION

Supplier selection is a crucial and complex aspect of the supply chain, as numerous factors impact a company's overall performance and competitiveness [1]. The capability of suppliers to supply the company's raw material requirements with high quality, timeliness, and delivery quantity is critical to preserving operational efficiency [2]. Therefore, regular evaluations of suppliers are necessary to create a priority list based on their performance [3, 4]. The standard of raw materials and services provided by the suppliers has an immediate impact on the quality of the products it produces. The relationship between product quality and supplier offerings emphasizes the critical need of a thorough and strategic supplier evaluation process to support the company's long-term competitiveness and market success [5]. A well-structured supplier selection approach guarantees that the company works with capable suppliers, thereby strengthening its manufacturing process and overall supply chain operations.

As the industrial world becomes more competitive, companies are increasingly recognizing the significance of environmental factors [6]. Beyond enhancing the company's reputation, the primary reason for choosing green suppliers is to minimize the environmental impact resulting from the raw material production process [7]. Such environmental implications can emerge in different forms, including dust emissions from high-speed machines, liquid waste generated during dyeing process, and solid waste consisting of unused fabric scraps. The selection of green suppliers is an important activity that goes beyond the typical considerations of economic and social dimensions, emphasizing the fundamental relevance of environmental aspects [8]. The primary purpose of green supplier selection is to help businesses achieve a harmonious balance in their performance across economic, social, and environmental aspects while limiting negative environmental consequences produced by their products and services [9].

In addressing the multi-dimensional nature of Green Supplier Selection (GSS), the multi-criteria decision-making (MCDM) methods have been widely employed to capture the trade-offs among economic, environmental, and social criteria. The MCDM provides a structured framework that enables decision-makers to evaluate multiple and often conflicting criteria simultaneously, thereby producing more rational and transparent decisions compared to intuitive or ad hoc approaches [10]. Among the MCDM Approaches, the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Data Envelopment Analysis (DEA) have been extensively applied in supplier evaluation and selection processes. AHP is particularly valuable in deriving priority weights from expert judgments through pairwise comparisons in qualitative criteria such as environmental management capability or supplier commitment to sustainability must be quantified. Moreover, TOPSIS is known for its ability to rank alternatives by measuring their relative closeness to an ideal solution, thus offering clear discrimination between competing suppliers. DEA, on the other hand, is often used to benchmark suppliers’ efficiency based on multiple input-output relationships, allowing for performance assessment in complex supply chains [11].

Despite their wide adoption, relying on a single MCDM technique presents several limitations. For instance, AHP is prone to inconsistencies when experts are required to provide a large number of pairwise comparisons, and its effectiveness decreases when handling vague or imprecise data [12]. TOPSIS, while efficient in ranking, is sensitive to normalization methods and may produce rank reversals if criteria weights are not robustly defined [13]. DEA, although powerful for efficiency analysis, may lack discriminatory power when many suppliers are evaluated, particularly when the number of criteria is large relative to the number of decision-making units. Furthermore, traditional crisp MCDM models assume that decision-makers can provide precise numerical judgments, which is rarely the case in practice. In green supplier selection, assessments often involve linguistic terms such as “moderate waste management” or “high compliance with environmental standards,” which introduce inherent subjectivity and uncertainty [14]. These methodological limitations underscore the need for hybrid and uncertainty-aware decision-making frameworks that combine the strengths of different MCDM approaches while addressing their respective shortcomings.

To address methodological gaps, the study proposes a hybrid decision-making framework that integrates fuzzy Delphi, fuzzy AHP, and fuzzy TOPSIS. Fuzzy Delphi refines and validates evaluation criteria through expert consensus, ensuring relevance and completeness. Fuzzy AHP assigns criterion weights under uncertainty, while fuzzy TOPSIS ranks supplier alternatives according to proximity to ideal solutions. The integrated framework strengthens methodological rigor, reduces subjectivity, and improves robustness in decision outcomes, enabling organizations to select suppliers consistent with both economic performance and environmental sustainability within sustainable supply chain management.

# RESEARCH METHODOLOGY

The research framework shown in Fig. 1 illustrates the sequential integration of the Fuzzy Delphi, AHP, and TOPSIS methodologies. The fuzzy Delphi method is employed to define relevant criteria and sub-criteria for green supplier selection. Subsequently, the fuzzy AHP method is utilized to determine the relative importance of each criterion and sub-criterion. Finally, the fuzzy TOPSIS method is to rank suppliers based on their performance relative to predefined criteria and sub-criteria.

**Stage 1.** The fuzzy Delphi approach combines fuzzy theory with the Delphi method. The steps involved in the fuzzy Delphi procedure are outlined as follows [15].

*Step 1.1* Identify the relevant the criteria and the sub-criteria for the company by proposing a list obtained from previous research. Develop a questionnaire and administer it to three stakeholders: the owner and two personnel from quality control. Assess the proposed the criteria and the sub-criteria regarding their relevance to the company's needs.

*Step 1.2* Assess the relevant sub-criteria with the help of company experts. These experts assess a list of sub-criteria by filling out the provided questionnaire. The questionnaire responses will be evaluated through the fuzzy Delphi approach to identify appropriate sub - criteria for the company.

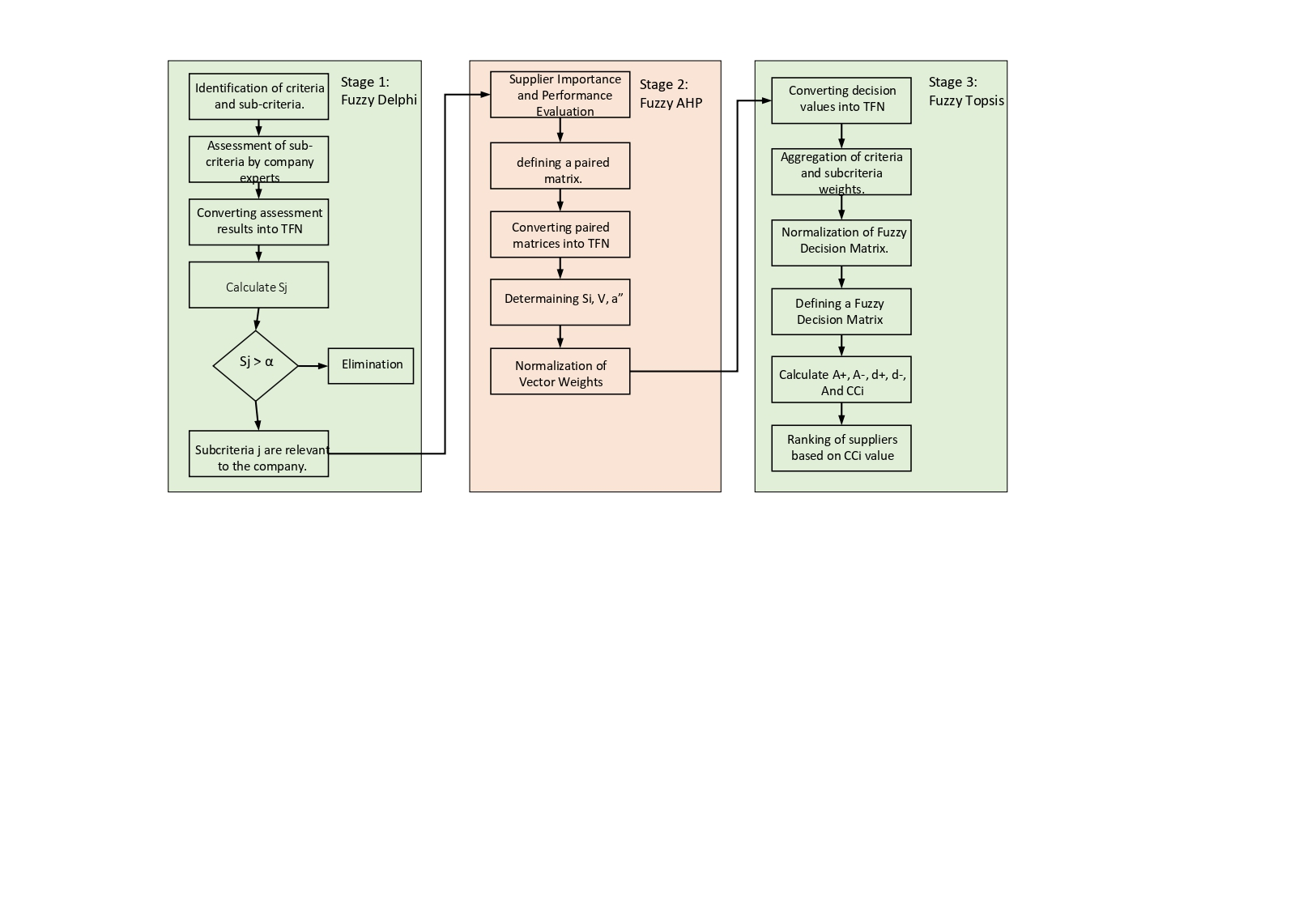
Step 1.3 Convert the assessment results into Triangular Fuzzy Numbers (TFNs). This process pertains to the linguistic scale in [Table 1](#table1).

**TABLE 1.** Fuzzy Delphi linguistic scale

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Linguistic Scale** | **Highly Important** | **Important** | **Medium** | **Unimportant** | **Highly Unimportant** |
| TFN | 0.7, 0.9, 0.9 | 0.5, 0.7, 0.9 | 0.3, 0.5, 0.7 | 0.1, 0.3, 0.5 | 0.1, 0.1, 0.3 |
| Source : Kumar, et al. [16] | | | | | |

*Step 1.4* Calculate the geometric mean based on the assessment results of = (,,) from the previous step. Where *k* represents theexpert, *k =* 1, 2, …, n, and *j* represents thesub-criteria, *j =* 1, 2, …, m.

|  |  |
| --- | --- |
| =  =  =  = (,,) | (1) |



**FIGURE 1.** Integration of fuzzy Delphi-AHP-TOPSIS Framework

*Step 1.5* Determine the value of using Eq. (2). If the value of ≥ α then criterion/sub-criterion *j* has been accepted. However, if ≥ α, then the *j*-th sub-criterion will be rejected [16]. The variable α represents the minimum acceptance threshold value ranging from 0.1 to 1. In this study, α was set to 0.6, derived from the smallest average "Important" value of 0.5 and the largest value of "Medium," which is 0.7.

|  |  |
| --- | --- |
| = | (2) |

**Stage 2**. The weights for each criterion and sub-criterion are established using the Fuzzy AHP. This analytical approach integrates the AHP method with fuzzy logic to offer a more comprehensive assessment. The following steps outline the Fuzzy AHP method [17]:

*Step 2.1* Convert the linguistic scale from the assessment importance to Triangular Fuzzy Number (TFN) by referring to Table 2. These numbers are defined by three real values, denoted as (*l*, *m*, *u*).The *l, m, u* parameters represent the smallest possible value, the most likely value, and the largest possible value that describe a fuzzy event.

*Step 2.2* Calculate fuzzy synthetic value (*Si*) using Eq. (4).

|  |  |
| --- | --- |
|  | (3) |
| *Si* = | (4) |

*Step 2.3* Calculate the degree of possibility (V). If M1 = (, , ) dan M2 = (, , ), the equation of the degree of possibility are as follows:

|  |  |
| --- | --- |
| V (M ≥ M1) = | (5) |
| V (M2 ≥ M1) = | (6) |

**TABLE 2.** Fuzzy AHP linguistic variable

|  |  |  |
| --- | --- | --- |
| ***Crisp Number*** | **Linguistic Scale** | **TFN** |
| 1 | Equal importance | (1,1,1) |
| 2 | Equal to moderate importance | (1,2,3) |
| 3 | Moderate importance | (1,3,5) |
| 4 | Moderate to strong importance | (2,4,6) |
| 5 | Strong importance | (3,5,7) |
| 6 | Strong to very strong importance | (4,6,8) |
| 7 | Very strong importance | (5,7,9) |
| 8 | Very to extremely importance | (6,8,9) |
| 9 | Extremely importance | (7,9,9) |
| Reciprocals of above | | |

*Step 2.4* Assume that d’(Ai) = min V(Si ≥ Sj) for i=1,2....,n and j =1, 2, ..., m; j ≠ i. Then, the weight vector is given by:

 (7)

*Step 2.5* Normalize the weight vector by employing Eq. (8). Where Wis a non-fuzzy number that gives the weight of criteria.

|  |  |
| --- | --- |
| *d*() = | (8) |
| *W* = | (9) |

Stage 3. The steps in the Fuzzy TOPSIS method are outlined below [18]:

*Step 3.1* Determine alternatives, criteria, and decision makers which are *m* defined as number of alternatives, *n* defined as number of criteria, and *k* defined as number of decision maker.

*Step 3.2* Transform the decision values into Triangular Fuzzy Numbers (TFN) using linguistic variables. Subsequently, the obtained questionnaire results for supplier performance assessment are converted into TFN format, referencing [Table 3](#table3) and [Table 4](#table4).

**TABLE 3.** Linguistic Variable of Benefit Criteria for Fuzzy TOPSIS

|  |  |
| --- | --- |
| **Linguistic Variable** | **TFN** |
| Very poor (VP) | (1,1,3) |
| Poor (P) | (1,3,5) |
| Fair (F) | (3,5,7) |
| Good (G) | (5,7,9) |
| Very good (VG) | (7,9,9) |

Source: Alptekin, et al. [19]

*Step 3.3* Calculate the aggregation of sub-criteria weights and the assessment results of supplier alternatives.

|  |  |
| --- | --- |
| = [ (+) (+) … (+) | (9) |
| = [ (+) (+) … (+) | (10) |

**TABLE 4.** Linguistic Variable of Cost Criteria for Fuzzy TOPSIS

|  |  |
| --- | --- |
| **Linguistic Variable** | **TFN** |
| Very Poor (VP) | (7,9,9) |
| Poor (P) | (5,7,9) |
| Fair (F) | (3,5,7) |
| Good (G) | (1,3,5) |
| Very Good (VG) | (1,1,3) |

*Step 3.4* Normalize the fuzzy decision matrix = . The calculations are conducted using Eq. (11) and   
Eq. (12).

|  |  |
| --- | --- |
| *=* , *j𝜖 B* |  |
| = , *j𝜖 B* | (11) |
| *=* , *j𝜖 C* |  |
| = , *j𝜖 C* | (12) |

*Step 3.5* Calculate the decision matrix (), using Eq. (13).

|  |  |
| --- | --- |
| = (x) *i =* 1, 2, …, m; *j =* 1, 2, …, n  = | (13) |

*Step 3.6* Calculate the positive and negative ideal solution matrix ( and ).

|  |  |
| --- | --- |
| = + + … + | (14) |
| = + + … + | (15) |

*Step 3.7* Calculate the distance between the value of each positive alternative () and the distance between the value of each negative alternative ().

|  |  |
| --- | --- |
| = | (16) |
| = | (17) |

*Step 3.8* Calculate the proximity coefficient for each existing alternative.

|  |  |
| --- | --- |
| = | (18) |

*Step 3.9* Green suppliers are ranked based on values. The values obtained are subsequently sorted in descending order to determine the priority sequence of supplier alternatives.

# RESULT AND DISCUSSION

An integrated Fuzzy Delphi-AHP-TOPSIS approach was applied for selecting green suppliers in a case study conducted at a garment company.

**Stage 1**. In this study, criteria and sub-criteria relevant to the company are identified through a questionnaire completed by internal experts. Prior to distributing the questionnaire, the researcher developed several sub-criteria based on a thorough review of recent and prior research, and then assessed their relevance to the company. The responses from the questionnaire were analyzed using the fuzzy Delphi method, and the resulting data are presented in Table 5.

**TABLE 5.** Calculation results of fuzzy Delphi

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Criteria** | **Sub-Criteria** | **Code** | **Sj** | **α** | **Decision** |
| Cost | Product Price [20] | CO1 | 0.744 | 0.6 | Ac. |
| Delivery Cost [21] | CO2 | 0.611 | 0.6 | Ac. |
| Payment Method [22] | CO3 | 0.611 | 0.6 | Ac. |
| Discount [23] | CO4 | 0.411 | 0.6 | Re. |
| Quality | Product Conformity with Specifications [22] | QU1 | 0.656 | 0.6 | Ac. |
| Consistency of Product Quality [22] | QU2 | 0.744 | 0.6 | Ac |
| Low Defect Rate [20, 24] | QU3 | 0.611 | 0.6 | Ac. |
| Delivery | Accuracy of Delivery Quantity [22] | DL1 | 0.611 | 0.6 | Ac. |
| Timeliness of Delivery [20] | DL2 | 0.633 | 0.6 | Ac. |
| Distance to Supplier Location [18] | DL3 | 0.611 | 0.6 | Ac. |
| Service | Communication [25] | SV1 | 0.722 | 0.6 | Ac. |
| Responsiveness and flexibility [26] | SV2 | 0.633 | 0.6 | Ac. |
| Information Disclosure [27] | SV3 | 0.633 | 0.6 | Ac. |
| Replacement of Defective Product [22] | SV4 | 0.611 | 0.6 | Ac. |
| Environmental | Environment-related Certificates [28] | EV1 | 0.611 | 0.6 | Ac. |
| Green Packaging [28] | EV2 | 0.611 | 0.6 | Ac. |
| The Use of Green Transport Modes/Equipment [28] | EV3 | 0.411 | 0.6 | Re |
| Reverse Logistic [28] | EV4 | 0.3 | 0.6 | Re |
| Green Material Selection [23] | EV5 | 0.7 | 0.6 | Ac. |
| Green Image [28] | EV6 | 0.611 | 0.6 | Ac. |
| Green Purchasing [28] | EV7 | 0.522 | 0.6 | Re. |
| Green Design [28] | EV8 | 0.411 | 0.6 | Re. |

Based on [Table 5](#table5), it was found that out of the total 22 sub-criteria evaluated, 17 were accepted (Ac), while 5 sub-criteria were rejected (Re). The rejected sub-criteria were identified as irrelevant to the company and are as follows: discounts (CO4) with a significance value of 0.411, the use of green transport modes/equipment (EV3) with a significance value of 0.411, reverse logistics (EV4) with a significance value of 0.3, green purchasing (EV7) with a significance value of 0.522, and green design (EV8) with a significance value of 0.411.

**Stage 2**. The weight calculation results for each criterion and sub-criterion using the fuzzy AHP method are presented in [Table 6](#table6).

The analysis of criterion weights shows that the quality criterion (QU) has the highest weight at 0.305, followed by the cost criterion (CO) in second place with a weight of 0.266. The delivery criterion (DL) is third with a weight of 0.219, while the service criterion (SV) is fourth with a weight of 0.160. The environmental criterion (EV) ranks fifth with a weight of 0.050. Thus, the quality criterion is the top priority, followed by cost, delivery, service, and environmental criteria in that order

The sub-criteria were ranked according to their respective weights, indicating their importance in the evaluation process. "Product Conformity with Specifications" (QU1) had the highest weight of 0.111, making it the most influential sub-criteria. The "Consistency of Product Quality" sub-criterion (QU2) followed closely with a weight of 0.107, highlighting its significant impact on the evaluation. The "Product Price" sub-criterion (CO1) also received considerable attention, with a weight of 0.100. "Delivery Cost" (CO2) was deemed vital with a weight of 0.089, emphasizing cost-effectiveness in transportation and logistics. Finally, "Low Defect Rate" (QU3) had a weight of 0.087, underscoring its crucial role in ensuring product quality and reliability

**TABLE 6.** Calculation results of fuzzy Delphi

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Criteria** | **Weight** | **Sub-Criteria** | **Code** | **Weight** | **Final Weight** |
| Cost | 0.266 | Product Price | CO1 | 0.377 | 0.100 |
| Delivery Cost | CO2 | 0.334 | 0.089 |
| Method of Payment | CO3 | 0.289 | 0.077 |
| Quality | 0.305 | Product Conformity with Specifications | QU1 | 0.364 | 0.111 |
| Consistency of Product Quality | QU2 | 0.350 | 0.107 |
| Low Defect Rate | QU3 | 0.286 | 0.087 |
| Delivery | 0.219 | Accuracy of Delivery Quantity | DL1 | 0.382 | 0.084 |
| Timeliness of Delivery | DL2 | 0.369 | 0.081 |
| Distance to Supplier Location | DL3 | 0.249 | 0.055 |
| Service | 0.160 | Communication | SV1 | 0.276 | 0.044 |
| Responsiveness and Flexibility | SV2 | 0.268 | 0.043 |
| Information Disclosure | SV3 | 0.204 | 0.033 |
| Replacement of Defective Product | SV4 | 0.251 | 0.040 |
| Environmental | 0.050 | Environment-related Certificates | EV1 | 0.276 | 0.014 |
| Green Packaging | EV2 | 0.266 | 0.013 |
| Green Material Selection | EV5 | 0.256 | 0.013 |
| Green Image | EV6 | 0.207 | 0.010 |

**Stage 3**. The weights of the sub-criteria are then used to determine the priority ranking of the company's suppliers using the fuzzy TOPSIS method. A questionnaire about the performance of alternative suppliers is first distributed to the company to assess the current performance of its suppliers. Table 7 presents the fuzzy TOPSIS calculation results. Based on the priority ranking of the supplier alternatives, A2 ranks first with a value of 0.394. A1 is in second place with a value of 0.391, A4 is third with a value of 0.375, A3 is fourth with a value of 0.365, and A5 is fifth with a value of 0.355.

**TABLE 7.** Calculation results of fuzzy TOPSIS

|  |  |  |
| --- | --- | --- |
| **Green Supplier Alternative** |  | **Rank** |
| A2 | 0,394 | 1 |
| A1 | 0,391 | 2 |
| A4 | 0,375 | 3 |
| A3 | 0,365 | 4 |
| A5 | 0,355 | 5 |

# CONCLUSION

This study introduced a hybrid decision-making framework integrating fuzzy Delphi, fuzzy AHP, and fuzzy TOPSIS for green supplier selection in the garment industry. The approach demonstrated its ability to capture uncertainty in expert judgment, refine relevant criteria, and produce a structured supplier ranking. The results emphasized that quality, cost, and delivery remain the dominant determinants in supplier evaluation, while environmental considerations such as certifications and green packaging also contribute to sustainability performance. The framework’s application identified supplier A2 as the preferred partner, validating its effectiveness in supporting strategic procurement decisions. From a managerial perspective, the study underscores the need to strengthen supplier evaluation processes through systematic weighting of criteria and consistent monitoring of performance. The framework enables decision-makers to balance operational efficiency with environmental objectives, thereby enhancing supply chain resilience and sustainability. Future research may extend the model by incorporating social responsibility and innovation-related criteria, testing its applicability across diverse industries, and engaging multiple organizational functions to ensure broader consensus and alignment with long-term sustainability goals.

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