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Selection of Raw Material Suppliers For Yarn Based on Sustainable Supply Chain Management Criteria Using Fuzzy Analytical Hierarchy Process (FAHP) and TOPSIS Methods at PT XYZ

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ABSTRACT

The industrial revolution and mass production directly increased human productivity and significantly impacted the environment. Amid these environmental problems, companies created environmentally friendly production strategies and prioritized economic factors (profit) and how they impact the social environment. This makes sustainable supply chain management in Sustainable Supplier Selection (SSS) increasingly in demand because it can affect the company's environmental performance. Companies that can improve their environmental and social performance will be able to increase their competitive advantage and impact, increasing revenue, market share, and a more positive green image of the company. There is no research on sustainable supplier selection in the sarong industry, especially in Indonesia. Therefore, research is needed on the sector because it dramatically affects environmental performance. One of the companies engaged in the sarong industry is XYZ company. This study aims to evaluate Supplier performance based on sustainable aspects (economic, environmental, social) using the cut-off point method for selecting sub-criteria, FAHP for assigning sub-criteria weights, and TOPSIS for ranking Suppliers based on predetermined sub-criteria. As a result of data processing, suppliers are ranked based on their preferences. As a result, Supplier 2 (S2) ranked first with a preference value of 0.9210, followed by Supplier 1 (S1) with a preference value of 0.7514, Supplier 3 (S3) with a preference value of 0.3166, and Supplier 4 (S4) with a preference value of 0.00019.

Introduction

The industrial revolution and mass production directly increased human productivity and significantly impacted the environment (Jin et al., 2023). During periods of rapid economic development, there is a clear positive relationship between economic growth and increasing carbon emissions (Tang et al., 2022). Companies often ignore the benefits of environmental sustainability in their operations, preferring to focus on economic opportunities rather than environmental and social benefits (Chen et al., 2020). Pressure from society and the government forces companies to review their processes and supply chains (Yildiz & Sezen, 2019). Therefore, industry players need to integrate sustainable elements into their strategies.

Supplier selection is one of the main aspects of supply chain management (Fallahpour et al., 2019; Tirkolaee et al., 2020; (Muttaqin et al., 2024). Supplier selection aims to rank potential suppliers based on the desired criteria to provide the required raw materials (Grant et al., 2023). This process involves evaluating various criteria to decide which supplier is the most suitable (Josiah et al., 2024). Based on statistical data, around 65–75% of a company's capital costs are invested in purchasing raw materials (Li et al., 2020), showing how important an effective supplier selection process is. The role of suppliers is vital in achieving efficient supply chain goals, so supplier evaluation is a significant decision for managers in supply chain management (SCM) (Haleem et al., 2021; Sinaga & Octo Yuneta, 2024). In addition, government attention to environmental issues has added to the challenges for companies in assessing the environmental impact of their suppliers. This creates the need to differentiate between sustainable procurement, production, eco-friendly packaging design, warehousing, distribution, and marketing practices (Acimovic et al., 2020). This trend encourages companies to consider sustainable supplier selection.

Decision Support System, better known as Decision Making System (DSS), was first introduced by Michael S. Scott Morton in 1970, through further developments known as Management Decision System (Wibowo et al., 2020). The Decision Support System concept is characterized by an interactive system that uses a computer to help decision-making by using data and models to solve unstructured and semi-structured problems (Sudipa et al., 2023; Mahmudi, 2022).

Previous studies have discussed various methods, criteria, and relevant sub-criteria to solve supplier selection problems. Azimifard et al. (2018) conducted a study on sustainable supplier selection using two methods, namely the AHP and TOPSIS methods, in the Iranian steel industry using sustainable criteria. In the following year, Mohammed et al. (2019) studied supplier selection by applying the Fuzzy AHP and TOPSIS methods to determine the weight of importance on economic, environmental, and social criteria in a metal and iron industry case study. In the same year, Wang et al. (2019) studied the selection of 10 suppliers in the garment industry and found that the Fuzzy AHP and TOPSIS methods were practical approaches to determining the best supplier in multi-criteria decision-making. Both of these methods are very popular in solving decision-making problems with many criteria due to their high level of accuracy.

PT XYZ is a manufacturing company producing woven sarongs since 1996. The company makes woven sarongs using machine looms and non-machine looms. The company produces around 49,000 woven sarongs monthly using an average of 7 tons of yarn as its primary raw material. Currently, PT XYZ is working with four yarn suppliers to maintain a smooth supply of raw materials, namely Supplier 1, Supplier 2, Supplier 3, and Supplier 4. The company faces significant challenges to meet market demand, such as ensuring the availability of raw yarn materials and implementing a sustainable supply chain in supplier selection.

Currently, the company needs a comprehensive assessment system for selecting suppliers. It only considers affordable prices, appropriate specifications, and product quality. As a result, the economic aspect is the only priority criterion, so the company often works with suppliers at risk of causing losses. On average, 5% of total annual production experiences damage to raw materials during shipping due to overloading and transportation that does not meet safety standards. The supplier's transport vehicles also do not meet emission standards, which impacts increasing pollution around the factory. In addition, the company produces around 3 tons of cardboard yarn packaging waste each year that needs to be optimally managed, thus increasing inefficiency in the business process. Some problems were also caused by work accidents on the supplier side, which resulted in delays in the delivery of raw materials. There were 19.8% delays during 2023, further exacerbating the production schedule's obstacles. This strengthens the urgency of using economic (E), environmental (L), and social (S) criteria.

Sustainability is usually operationalized in operations and SCM areas through the triple bottom line or TBL (Elkington, 1988). The sustainability aspect of profit in TBL can be seen through the application of innovation and technology, collaboration, knowledge management, quality management, product management, sustainable supply chains, and sustainability reports (Dari, 2024). The people aspects discussed include corporate governance, motivation and incentives, occupational health and safety, human capital development, and human rights (Mamede de Andrade et al., 2020). Meanwhile, the planet aspect focuses on the company's effectiveness in managing the impact of its operations on the environment (Edeigba & Arasanmi, 2022).

The abovementioned problems will produce various decision choices based on many considerations. Fuzzy AHP combines the AHP method with the Fuzzy approach, especially using a Triangular Fuzzy Number (TFN) in a pairwise comparison scale. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) selects the best alternative with the smallest distance from the ideal solution obtained and the most significant distance from the negative ideal solution (Rozi et al., 2019). The use of the FAHP method integration with TOPSIS was chosen because it can eliminate subjectivity and obtain results with a high level of accuracy. This study can be the basis for selecting suppliers to realize a sustainable supply chain at PT XYZ using the Fuzzy Analytical Hierarchy Process (FAHP) and TOPSIS methods. By doing this, companies can strengthen their business sustainability, build customer trust, and contribute to economic development, a clean environment, and a just society (Pedroso et al., 2021). By implementing sustainable supply chain practices, companies are investing in their future and our planet's future.

MATERIALS AND METHODS

One of the determining factors in selecting the best supplier is the application of multicriteria decision-making methods (Arundaa & Kalua, 2023). This research was conducted in the woven sarong manufacturing industry in Gresik, East Java. Research data were collected through company document analysis, interviews, and questionnaire distribution at PT XYZ.

The supplier determination process begins with an interview with the Head of Purchasing to identify problems related to the procurement system. This step aims to obtain in-depth information and set priorities when selecting supplier sub-criteria. This study uses three types of questionnaires, namely:

1. Questionnaire to determine sub-criteria,
2. Questionnaire to determine the importance and weight of each criterion, and
3. Questionnaire to assess yarn material suppliers.

The questionnaire respondents included the director, head of purchasing, and one purchasing staff. These three questionnaires were processed sequentially. In this study, the author used the cut-off point method, Fuzzy AHP, and TOPSIS as data processing methods.

Cut Off Point

Cut Off Point is a method used to sort the use or use of criteria for consideration in decision-making problems (Sari & Mubaroq, 2023; (Laurentia & Septiani, 2023). In addition, this method is also used to ensure the degree of need for criteria, whether they are essential or not (Gulo & Murni, 2023). The COP method divides the assessment into three parts: criteria considered to have a very important level of significance will be given a value or weight of 3, criteria considered to have a fairly important level of significance will be given a weight value of 2, and criteria considered to have an unimportant level of significance will be given a weight value of 1 (Siagian et al., 2023). All criteria are sorted from highest to lowest. Then, the Natural Cut Off Point is determined with the following equation:

$$Natural\ Cut\ Off\ Point = \left(\frac{\bar{x}\ max + \bar{x}\ min}{2}\right)$$

Analytical Hierarchy Process (AHP)

AHP was developed by Thomas L. Saaty in 1970 and is a well-known and widely used multicriteria decision-making (MCDM) technique (Saaty, 2008). AHP helps to structure the problem and is used in this study to determine the weight of the criteria in sustainable supplier selection (Çalık, 2021; Thakkar, 2021; (Irianto et al., 2022). This method structures problems hierarchically, including criteria, sub-criteria, and alternatives. There are six steps in calculating AHP (Saaty, 1988), namely:

1. Defining and understanding the problem by creating a hierarchy of objectives, supplier criteria, supplier sub-criteria, and existing suppliers, which are then arranged in a hierarchical form.
2. Once the multicriteria problem is modelled in a hierarchy, the next stage is to perform pairwise comparisons to determine the weight of each criterion and subcriterion.
3. Using normalized pairwise comparisons of matrices, multiply the eigenvalues of the vectors by finding the consistency value.
4. Repeat steps 2 and 3 for each component in the hierarchy.
5. Calculate the eigenvalues (λ max) by dividing the sum of each row by the total.
6. A consistency test is carried out to determine whether the data obtained is valid. In finding the CI value, knowing the Number of criteria/sub-criteria used (n) is necessary. The hierarchical consistency test has a provision, the CR value < 0.1. The CR value is obtained from:

$$CI = \frac{(\lambda max - n)}{(n-1)}$$

$$CR = \frac{CI}{RI}$$

Information:

CI = Consistency index

λ_{max} = Eigenvalue

n = Number of activities/elements being compared in the matrix

CR = Consistency ratio

RI = random index value

Fuzzy AHP

In this study, the Fuzzy AHP approach uses the expansion method developed by Chang, by applying triangular Fuzzy numbers (TFN) to determine the Fuzzy weights of the factors involved (Chang, 1996). The calculation steps to obtain the assessment weights using the Fuzzy AHP method, according to Buckley (Broto et al., 2020) are as follows:

1. Composing and building a hierarchy of a problem.
2. Pairwise comparisons were performed using the Triangular Fuzzy Number (TFN) scale.
3. Determining the pairwise comparison matrix

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \cdots & \tilde{a}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \cdots & \tilde{a}_{nn} \end{bmatrix}$$

Where:

$\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}), i = 1,2, \dots, n, j = 1,2, \dots, n$

4. Calculate the geometric mean of the Fuzzy comparison values for each criterion with the following equation:

$$\tilde{r}_l = \left(\coprod_{j=1}^{n} \tilde{a}_{ij}\right)^{1/n}$$

Information:

n = Amount of data

$\tilde{a}_{ij}$ = Respondent data

$\tilde{r}_l$ = Geometric mean

5. Calculate the Fuzzy weight for each criterion with the following equation:

$\widetilde{W}_l = \tilde{r}_1 \otimes (\tilde{r}1 \otimes \tilde{r}2 \otimes \dots \otimes \tilde{r}n)^{-1} = (lw_i, mw_i, uw_i)$

Information:

$\widetilde{W}_l$ = Fuzzy Weight

$\tilde{r}_1$ = Average geometric value

6. Because $\widetilde{W}_i$ it is still in the form of a Fuzzy triangular, it is necessary to calculate the non-Fuzzy or de-fuzzified weight using the center of area (CoA) method proposed by Chou and Chang with the following equation:

$$M_i = \frac{lw_i, mw_i, uw_i}{3}$$

Information:

M_i = Non Fuzzy weight

lw_i = Lower value

mw_i = Middle value

uw_i = Upper value

7. The Mi weight is a non-fuzzy number, so it is necessary to normalize it using the following equation:

$$N_i = \frac{M}{\sum_{i=1}^{n} M_i}$$

Information:

N_i = Final weight

Triangular Fuzzy Numbers are part of Fuzzy Set theory which is used to measure human subjective judgment with the help of language or linguistic terms (Sur et al., 2020).

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the important methods in multi-criteria decision analysis (MCDM), developed by Hwang and Yoon in 1981 (Sharma et al., 2020). This MCDM method is based on the concept that the selected factors must have the closest distance from the positive ideal solution and the furthest geometric distance from the negative ideal solution (Bera et al., 2022).

According to Do et al. (2024), in the TOPSIS technique, an alternative is considered optimal if it has the closest distance to the positive ideal solution and the furthest distance from the negative ideal solution. The advantages of the TOPSIS method are that the best alternative selected is a simple mathematical model, the calculations are easy, the logic is simple and easy to understand, and the most important assessment is the procedures being compared (Lestari et al., 2023). According to (Vafaei et al., 2021), quoted in the research of (Putri & Pulansari, 2022) the steps of the TOPSIS method are as follows:

1. Build a matrix for decision-making based on agreed supplier research.
2. Perform transformation on each element in the decision matrix to obtain normal results (normalization) using the formula below:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}^2}$$

Information:

r = Normalized matrix

Value j = 1,2,…,n (column)

Value i = 1,2,…,m (row)= 1,2,…,m (row)

3. Building a decision matrix with normalized weightings. The normalized decision matrix with the weights of each criterion determines the matrix.

$$y_{ij} = W_i \times r_{ij}$$

Information:

Y = Weighted normalized decision matrix

W = Preference weight of each criterion

r = Normalized matrix

4. Create a matrix of positive and negative ideal solutions, where A+ represents the positive ideal solution and A- represents the negative ideal solution.

$$A^+ = (Y_1^+, Y_2^+, \ldots, Y_3^+)\ \{(\max y_{ij} |\ j \in J), (\min y_{ij} |\ j \in J)\}$$
$$A^- = (Y_1^-, Y_2^-, \ldots, Y_3^-)\ \{(\min y_{ij} |\ j \in J), (\max y_{ij} |\ j \in J)\}$$

Information:

J = {j = 1, 2, … , n | j is the profit criterion}

J = {j = 1, 2, … , n | j is the cost criterion}

5. Calculate the distance between each value of the existing alternatives

$$D_i^+ = \sqrt{\sum_{j=i}^{n} (y_i^+ - y_i)^2}$$

$$D_i^- = \sqrt{\sum_{j=i}^{n} (y_{ij} - y_i^-)^2}$$

Information:

Value of i = 1, 2, 3, …, m

D = Distance of alternative values

y = Weighted normalized decision matrix value

6. Determine the preference value for each alternative with Vi values ranging from 0 to 1. The calculation of the Vi value follows the following formula:

$$Vi = \frac{D_i^-}{D_i^- + D_i^+}$$

Description:

V = Alternative proximity distance

D = Distance of alternative values

RESULTS AND DISCUSSION

The criteria and sub-criteria are based on TBL (Triple Bottom Lines) sustainability and consist of economic, social, industrial, and environmental aspects (Sen et al., 2019). Sub-criteria is determined by distributing questionnaìres to experts. The questionnaire will be used to determine the priority of the sub criìteriìa to be used in decision-making. There are three respondents or experts. Experts will assign importance to the factors on a scale of "Very Important", "Moderately Important", and "Not Important". In Table 1, the questionnaire results will be processed using the Cut-off Point method, eliìminating sub-criìteriìa wiìth values below Natural Cut Off Point.

Table 1. Average Importance Result with Cut-Off Point Method

No	Code	Criteria	Code	Sub Criteria	Respondents 1	2	3	Average
1	E1	Cost	E11	Product price	3	3	3	3.00
			E12	Shipping costs	2	3	3	2.67
			E13	Payment terms	3	3	2	2.67
			E14	Local business development	2	2	2	2.00
Natural Cut-Off Point Value								2.5
Selected sub-criteria								E11, E12, E13
2	E2	Quality	E21	Quality based on ISO	3	3	2	2.67
			E22	Maintenance and rejection rate	3	2	2	2.33
			E23	Total quality management (TQM)	3	3	2	2.67

No	Code	Criteria	Code	Sub Criteria	Respondents 1	2	3	Average
			E24	Adequate production facilities	2	3	3	2.67
		Natural Cut-Off Point Value						2.5
		Selected sub criteria						E21, E23, E24
3	E3	Service Performance	E31	Delivery Schedule	2	3	3	2.67
			E32	Geographic location	2	2	2	2.00
			E33	Provision of insurance guarantee	3	2	2	2.33
			E34	After-sales service	3	2	3	2.67
			E35	Problem handling	3	3	3	3.00
		Natural Cut-Off Point Value						2.5
		Selected sub-criteria						E31, E34, E35
4	E5	Flexibility	E41	Flexibility in providing discounts	2	3	3	2.67
			E42	Flexibility in ordering	3	3	2	2.67
			E43	Flexibility in delivery	3	3	2	2.67
		Natural Cut-Off Point Value						2.67
		Selected sub-criteria						E41, E42, E43
5	L1	Environmental management system	L11	Internal control process	2	2	2	2.00
			L12	Environmental protection plan	2	3	3	2.67
			L13	Environmental protection policy	3	3	2	2.67
			L14	ISO 14001 Certification	3	3	3	3.00
			L15	Environmental training for workers	3	2	1	2.00
		Natural Cut-Off Point Value						2.5
		Selected sub-criteria						L12, L13, L14
6	L2	Environmentally friendly manufacturing systems	L21	Pollution reduction	3	2	3	2.67
			L22	wastewater	2	3	3	2.67
			L23	Material storage	3	3	2	2.67
			L24	Storage management	3	2	3	2.67
			L25	Use of modern, efficient and environmentally friendly transportation	3	2	3	2.67
			L26	Use of environmentally friendly fuels	2	1	2	1.67
		Natural Cut-Off Point Value						2.17
		Selected sub-criteria						L21, L22, L23, L24, L25
7	L3	Environmentally friendly	L31	Use of environmentally friendly materials	3	3	2	2.67

No	Code	Criteria	Code	Sub Criteria	Respondents			Average
					1	2	3	
		competence	L32	Recycling capability	2	2	1	1.67
			L33	Eco-friendly packaging	3	3	3	3.00
			L34	Responsiveness	3	3	2	2.67
				Natural Cut-Off Point Value				2.33
				Selected sub-criteria				L31, L33, L34
8	S1	Employment practices	S11	Job stability	3	2	3	2.67
			S12	Job opportunities	2	1	2	1.67
			S13	Flexible working arrangements	3	2	2	2.33
			S14	Standard working hours	2	3	2	2.33
				Natural Cut-Off Point Value				2.17
				Selected sub-criteria				S11, S13, S14
9	S2	Populatiion dynamics	S21	Gender equality in job positions	2	3	3	2.67
			S22	Equal distribution of age in each population group	2	3	2	2.33
			S23	Equal distribution of birthplaces of each population group	2	1	2	1.67
			S24	Income equaliity	3	2	3	2.67
				Natural Cut-Off Point Value				2.17
				Selected sub criiteriia				S21, S22, S24
10	S3	Occupatiional Health and Safety	S31	Health Insurance	1	2	3	2.00
			S32	K3 Training	3	3	3	3.00
			S33	Health and Safety Management (OHSAS) 18001	3	3	3	3.00
			S34	Occupational health and safety conditions standards	3	3	2	2.67
			S35	Health and safety incidents	3	3	2	2.67
				Natural Cut-Off Point Value				2.5
				Selected sub criiteriia				S32, S33, S34, S35
11	S4	Education and training	S41	Skills in work	3	3	2	2.67
			S42	Workers' education level	2	2	2	2.00
			S43	Employee participation rate in self-development courses	2	3	3	2.67
			S44	Level of worker participation in training	2	3	3	2.67
				Natural Cut-Off Point Value				2.33
				Selected sub-criteria				S41, S43, S44

The results of the criteria and sub-criteria, according to the choices of the three respondents in Table 1, were then entered into a sequential hierarchical arrangement to facilitate the completion of the next stage of processing in the second questiìonnaiìre usiìng the FAHP method. This first questionnaire shows that the natural exclusion of criteria and sub-criteria makes sense for the classification scale because, on average, all respondents accept using criteria and sub-criteria to evaluate supplier performance. The sequential hierarchical structure is attached in Figure 1.

Pairwise Comparison Matrix

A pairwise comparison matrix of the criteria was obtained from recapitulating respondent assessments. The results of sustainable criteria are entered into the pairwise comparison matrix shown in Table 2. Furthermore, the normalization matrix is constructed by dividing the column elements by the total column value, as shown in Table 3. After obtaining the normalization value, the next step is to find the priority weight value. The priority weight value is obtained by calculating the average value of each row of the normalization value.

Figure 1. Yarn Supplier Selection Hierarchy Structure

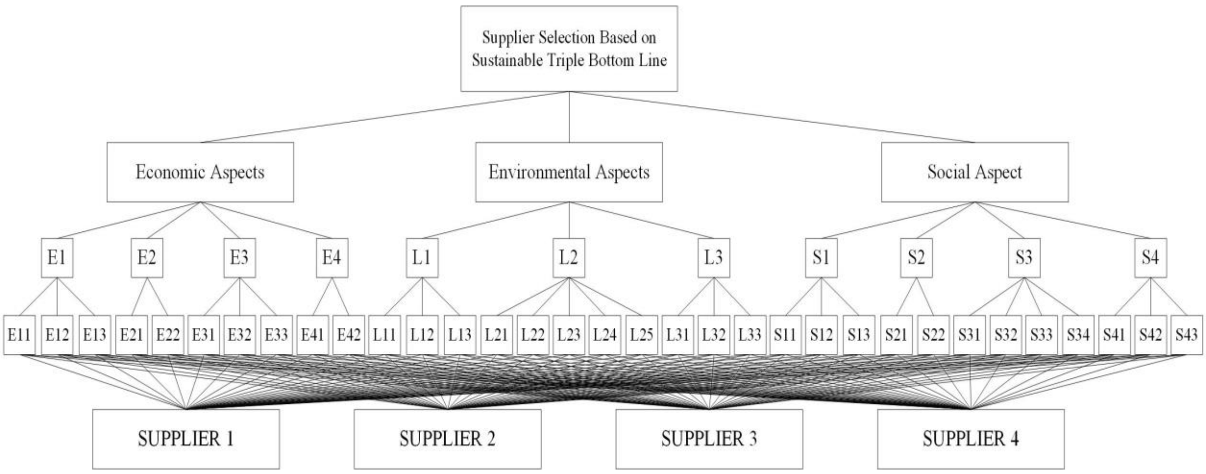

Table 2. Matrix of Pairwise Comparison Criteria

Criteria	E1	E2	E3	E4	L1	L2	L3	S1	S2	S3	S4
E1	1	1	2	7	5	5	5	3	5	7	5
E2	1	1	3	7	4	3	3	3	7	9	7
E3	1/2	1/3	1	3	1/3	1/3	1/3	1/2	3	1/3	3
E4	1/7	1/7	1/3	1	1/5	1/5	1/5	1/3	1/2	1/3	1/2
L1	1/5	1/4	3	5	1	1	1	1	3	1/2	3
L2	1/5	1/3	3	5	1	1	1	2	3	1/3	5
L3	1/5	1/3	3	5	1	1	1	3	2	2	3
S1	1/3	1/3	2	3	1	1/2	1/3	1	1/2	1	2
S2	1/5	1/7	1/3	2	1/3	1/3	1/2	2	1	1/7	3
S3	1/7	1/9	3	3	2	3	1/2	1	1/5	1	3
S4	1/5	1/7	1/3	2	1/3	1/5	1/3	1/2	1/3	1/3	1
Total	4.12	4.12	21.00	43.00	16.20	15.57	13.20	17.33	25.53	21.98	35.50

Table 3. Criteria Data Normalization Results

Criteria	E1	E2	E3	E4	L1	L2	L3	S1	S2	S3	S4	Priority Weight
E1	0.243	0.243	0.095	0.163	0.309	0.321	0.379	0.173	0.196	0.319	0.141	0.235
E2	0.243	0.243	0.143	0.163	0.247	0.193	0.227	0.173	0.274	0.410	0.197	0.228
E3	0.121	0.081	0.048	0.070	0.021	0.021	0.025	0.029	0.117	0.015	0.085	0.058
E4	0.035	0.035	0.016	0.023	0.012	0.013	0.015	0.019	0.020	0.015	0.014	0.020
L1	0.049	0.061	0.143	0.116	0.062	0.064	0.076	0.058	0.117	0.023	0.085	0.077
L2	0.049	0.081	0.143	0.116	0.062	0.064	0.076	0.115	0.117	0.015	0.141	0.089
L3	0.049	0.081	0.143	0.116	0.062	0.064	0.076	0.173	0.078	0.091	0.085	0.092
S1	0.081	0.081	0.095	0.070	0.062	0.032	0.025	0.058	0.020	0.046	0.056	0.057
S2	0.049	0.035	0.016	0.047	0.021	0.021	0.038	0.115	0.039	0.007	0.085	0.043
S3	0.035	0.027	0.143	0.070	0.123	0.193	0.038	0.058	0.008	0.046	0.085	0.075
S4	0.049	0.035	0.016	0.047	0.021	0.013	0.025	0.029	0.013	0.015	0.028	0.026
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

After calculating the priority weight, the next step is calculating the lambda max (eigenvalue). Lambda max is obtained by multiplying the priority weight and the sum of the AHP pairwise matrices.

$\sum \lambda max$ = (0.243 x 4,212) + (0,243 x 4,12) + (0,095 x 21,00) + (0,163 x 43,00) + (0,309 + 16,20) + (0,321 + 15,57) + (0,379 + 13,20) + (0,173 + 17,33) + (0,196 + 25,53) + (0,319 + 21,98) + (0,141 + 35,50)

$\sum \lambda max$ = 12,394

After knowing the lambda max value, the Consistency Index (CI) and Consistency Ratio (CR) values are calculated as shown in Table 4. From the table, it is known that the CR value is 0.0923, which is below 0.1. Therefore, it can be concluded that the CR for comparing all criteria is consistent.

Table 4. Calculation Criteria Results AHP Method

λmax	RI	CI	CR
12,394	1,51	0,1394	0,0923

AHP calculations with the same steps as above were carried out to compare sub-criteria for each other criterion, and all the results were consistent.

Fuzzy Analytical Hierarchy Process

At this stage, data from respondents obtained through paired comparison questionnaires with the AHP scale will be converted into a Triangular Fuzzy Number (TFN) with the format (l, m, u). For example, converting AHP values to Fuzzy numbers in column E1 and row E2, where the E1-E2 value in the AHP comparison questionnaire is 1, after being converted to Fuzzy numbers (l, m, u) it will have a value of 1, 1, 1. If referring to column E1 row L1 with an AHP value of 5, if converted into Fuzzy number form (l, m, u), it will be 4,5,6, with lower (l)=4, middle (m)=5, and upper (u)=6. Table 5 shows the conversion of the AHP scale to the Fuzzy scale and its processing using the Fuzzy method for comparing criteria.

After converting the values into Triangular Fuzzy Numbers (TFN), the next step is to find the geometric mean value of the Fuzzy, which is shown in Table 6.

Table 5. TFN Data Criteria Conversion

Criteria	E1			E2			E3			E4			L1		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
E1	1	1	1	1	1	1	1	2	3	6	7	8	4	5	6
E2	1	1	1	1	1	1	2	3	4	6	7	8	3	4	5
E3	1/3	1/2	1	1/4	1/3	1/2	1	1	1	2	3	4	1/4	1/3	1/2
E4	1/8	1/7	1/6	1/8	1/7	1/6	1/4	1/3	1/2	1	1	1	1/6	1/5	1/4
L1	1/6	1/5	1/4	1/5	1/4	1/3	2	3	4	4	5	6	1	1	1
L2	1/6	1/5	1/4	1/4	1/3	1/2	2	3	4	4	5	6	1	1	1
L3	1/6	1/5	1/4	1/4	1/3	1/2	2	3	4	4	5	6	1	1	1
S1	1/4	1/3	1/2	1/4	1/3	1/2	1	2	3	2	3	4	1	1	1
S2	1/6	1/5	1/4	1/8	1/7	1/6	1/4	1/3	1/2	1	2	3	1/4	1/3	1/2
S3	1/8	1/7	1/6	1/9	1/9	1/8	2	3	4	2	3	4	1	2	3
S4	1/6	1/5	1/3	1/8	1/7	1/6	1/4	1/3	1/2	1	2	3	1/4	1/3	1/2

Criteria	L2			L3			S1			S2			S3			S4		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
E1	4	5	6	4	5	6	2	3	4	4	5	6	6	7	8	4	5	6
E2	2	3	4	2	3	4	2	3	4	6	7	8	9	9	9	6	7	8
E3	1/4	1/3	1/2	1/4	1/3	1/2	1/3	1/2	1	2	3	4	1/4	1/3	1/2	2	3	4
E4	1/6	1/5	1/4	1/6	1/5	1/4	1/4	1/3	1/2	1/3	1/2	1	1/4	1/3	1/2	1/3	1/2	1
L1	1	1	1	1	1	1	1	1	1	2	3	4	1/3	1/2	1	2	3	4
L2	1	1	1	1	1	1	1	2	3	2	3	4	1/4	1/3	1/2	4	5	6
L3	1	1	1	1	1	1	2	3	4	1	2	3	1	2	3	2	3	4
S1	1/3	1/2	1	1/4	1/3	1/2	1	1	1	1/3	1/2	1	1	1	1	1	2	3
S2	1/4	1/3	1/2	1/3	1/2	1	1	2	3	1	1	1	1/8	1/7	1/6	2	3	4
S3	2	3	4	1/3	1/2	1	1	1	1	1/6	1/5	1/4	1	1	1	2	3	4
S4	1/6	1/5	1/4	1/4	1/3	1/2	1/3	1/2	1	1/4	1/3	1/2	1/4	1/3	1/2	1	1	1

Table 6. Fuzzy Geometry Value

Criteria	l	m	u
E1	2.77	3.48	4.13
E2	2.83	3.51	4.13
E3	0.53	0.72	1.07
E4	0.24	0.30	0.41
L1	0.91	1.12	1.37
L2	0.96	1.23	1.53
L3	1.03	1.39	1.74
S1	0.60	0.82	1.15
S2	0.38	0.53	0.73
S3	0.67	0.88	1.13
S4	0.29	0.38	0.55
Total	11.20	14.36	17.93
Reverse	0.09	0.07	0.06
Increasing Order	0.06	0.07	0.09

The next step is to calculate the Fuzzy weight by multiplying the geometric value of each criterion by its increasing-order lower value. After the Fuzzy weight is known, defuzzification is carried out to combine the values from lower, middle, and upper to make one value using the centre-of-area method and defuzzification calculation values for all criteria can be seen in Table 7.

Table 7. M_i Value

Criteria	Mi
E1	0.00461
E2	0.00474
E3	0.00005
E4	0.00000
L1	0.00016
L2	0.00021
L3	0.00029
S1	0.00006
S2	0.00002
S3	0.00008
S4	0.00001
Total	0.01022

The final weight (N_i) is calculated by dividing each M_i criterion by the total M_i. Table 8 shows the results of the final weight (N_i) calculation.

Table 8. Final Weight (N_i)

Criteria	Ni
E1	0.451
E2	0.464
E3	0.005
E4	0.000
L1	0.016
L2	0.021
L3	0.028
S1	0.006
S2	0.002
S3	0.008
S4	0.001

Table 8 is the final weight result in the pairwise comparison of criteria. The weight value will then be calculated in combination with the weight value of the sub-criteria between criteria to determine the global weight value. The calculation using the same steps above is carried out on all sub-criteria. Table 9 summarises all criteria weights, sub-criteria, and global sub-criteria weights.

Ranking Supplier Based on TOPSIS Method

After determining the level of importance of supplier criteria and subcriteria based on sustainability aspects using the FAHP, the next step is to assess supplier performance based on the criteria and subcriteria determined from the previous survey. The data obtained is used to calculate the alternative normalization of each alternative based on the subcriteria that have been determined. Furthermore, a weighted normalization calculation is performed by multiplying the normalized decision matrix by the global weight of each subcriteria obtained from the FAHP results.

Table 9. Recapitulation of Criteria And Sub-Criteria Weights

No	Code	Criteria	Criteria Weight	Code	Sub Criteria	Sub Criteria Weight	Global Weight
					Economic Aspects		
1	E1	Cost	0.451	E11	Product priice	0.54398	0.24526
				E12	Shipping costs	0.27531	0.12413
				E13	Payment terms	0.18072	0.08148
2	E2	Quality	0.464	E21	Quality based on IiSO	0.51746	0.23994
				E22	*Total quality management* (TQM)	0.30888	0.14322
				E23	Adequate Production Facilities	0.17366	0.08052
3	E3	Service Performance	0.005	E31	Delivery schedule	0.57125	0.00262
				E32	After-sales service	0.16255	0.00074
				E33	Problem handling	0.26620	0.00122
4	E4	Flexibility	0.000	E41	Flexibility iin providing diiscounts	0.16172	0.00005
				E42	Flexibility in ordering	0.26994	0.00009
				E43	Flexibility in delivery	0.56834	0.00018
					Environmental Aspects		
1	L1	Enviironmental management system	0.016	L12	Environmental protection plan	0.10637	0.00168
				L13	Environmental protection policy	0.60311	0.00950
				L14	ISO 14001 Certification	0.29052	0.00458
2	L2	Environmentally friendly manufacturing systems	0.021	L21	Pollution reduction	0.34641	0.00712
				L22	wastewater	0.32276	0.00664
				L23	Material storage	0.33083	0.00680
				L24	Storage management	0.20648	0.00425
				L25	Use of modern, efficient and environmentally friendly transportatiion	0.11858	0.00244
3	L3	Environmentally friendly	0.028	L31	Use of environmentally friendly materials	0.42613	0.01190

No	Code	Criteria	Criteria Weight	Code	Sub Criteria	Sub Criteria Weight	Global Weight
		competence		L32	Eco-friendly packaging	0.42613	0.01190
				L33	Responsiveness	0.14773	0.00412
					Social Aspects		
1	S1	Employment practices	0.006	S11	Job stability	0.42613	0.00270
				S12	Flexible working arrangements	0.14773	0.00094
				S13	Standard working hours	0.42613	0.00270
2	S2	Population dynamics	0.002	S21	Gender equality in job positions	0.36686	0.00062
				S22	Equal distribution of age in each population group	0.11608	0.00019
				S23	Income equality	0.51707	0.00087
3	S3	Occupational Health and Safety	0.008	S31	K3 Training	0.36275	0.00276
				S32	Health and Safety Management (OHSAS) 18001	0.30946	0.00235
				S33	Occupational health and safety conditions standards	0.32779	0.00249
				S34	Health and safety incidents	0.14809	0.00113
4	S4	Education and training	0.001	S41	Skills in work	0.31542	0.00021
				S42	Employee participation rate in self-development courses	0.27297	0.00018
				S43	Level of worker participation in training	0.41161	0.00028

After receiving the weighted normalization value, the next step Table 10 is to determine the positive ideal solution (A^+), which is the maximum value of the weighted normalization for each criterion, and the negative ideal solution (A^-), which is the minimum value of the weighted normalization for each criterion. This stage ensures supplier evaluation is carried out systematically, objectively, and by sustainability principles. The result are as shown in Table 10.

Table 10. Positive ideal solution and negative ideal solution

No	Sub Criteria	Ideal Solution	
		A+ Max	A- Min
1	E11	0.1591	0.0796
2	E12	0.0757	0.0568
3	E13	0.0567	0.0284
4	E21	0.1357	0.1018
5	E22	0.0929	0.0465
6	E23	0.0456	0.0342
7	E31	0.0017	0.0008

No	Sub Criteria	Ideal Solution	
		A+ Max	A- Min
8	E32	0.0005	0.0002
9	E33	0.0008	0.0004
10	E41	0.0000	0.0000
11	E42	0.0000	0.0000
12	E43	0.0001	0.0001
13	L11	0.0008	0.0008
14	L12	0.0058	0.0043
15	L13	0.0026	0.0019
16	L21	0.0050	0.0025
17	L22	0.0036	0.0024
18	L23	0.0041	0.0020
19	L24	0.0025	0.0013
20	L25	0.0016	0.0011
21	L31	0.0077	0.0039
22	L32	0.0070	0.0047
23	L33	0.0029	0.0014
24	S11	0.0016	0.0012
25	S12	0.0006	0.0004
26	S13	0.0015	0.0010
27	S21	0.0004	0.0003
28	S22	0.0001	0.0001
29	S23	0.0006	0.0003
30	S31	0.0016	0.0008
31	S32	0.0014	0.0007
32	S33	0.0015	0.0007
33	S34	0.0007	0.0004
34	S41	0.0001	0.0001
35	S42	0.0001	0.0001
36	S43	0.0002	0.0001

Then, calculate the distance value of each alternative by comparing the relative proximity to the positive ideal (A+) and negative ideal ($A-$) shown in Table 11. The next step is to assign a value to each alternative according to its preference. A preference value refers to a value that describes the value of the distance of an alternative's proximity to its ideal solution. Alternatives (Ai) with higher preference values will be preferred. Data related to the preference values of each alternative can be seen in Table 12.

Table 11. Alternative Distance for Sustainable Supplier Evaluation

Supplier	Da+	Da-
S1	0.00097085	0.00293465
S2	0.00037454	0.00436722
S3	0.00229655	0.00106401
S4	0.00548709	0.00000105

Table 12. Vi value and the rank of sustainable supplier

Rank	Supplier	Vi
1	S2	0.92101237
2	S1	0.75141462
3	S3	0.31661678
4	S4	0.00019168

Data processing results produce a supplier preference order based on the highest to lowest values. Supplier 2 (S2) is ranked first with a preference value of 0.9210, followed by Supplier 1 (S1) in second place with a preference value of 0.7514, Supplier 3 (S3) in third place with a preference value of 0.3166, and Supplier 4 (S4) in fourth place with a preference value of 0.00019. The resulting best supplier order already covers all the criteria and sub-criteria determined in this study. Through this approach, companies can choose suppliers who not only have the best performance but also comply with the principles of sustainability that include economic, environmental, and social aspects.

CONCLUSION

Based on the data processing results from the three stages of the questionnaire survey, this study concluded several key findings. The Cut Off Point method was used in the first survey to validate sustainability sub-criteria relevant to the company's condition, resulting in 11 criteria and 36 sub-criteria from economic, environmental, and social aspects. With the AHP method, all criteria and sub-criteria have a CR value $\leq$ 0.1, indicating consistency of assessment and validity without needing revision. These criteria and sub-criteria weights are then converted to Triangular Fuzzy Numbers (TFN) to calculate the global weight.

The TOPSIS method is used to determine the ranking of suppliers based on the preference coefficient for sustainability sub-criteria. As a result, Suppliier 2 (S2) iis ranked first with a preference value of 0.9210, followed by Supplier 1 (S1) with 0.7514, Supplier 3 (S3) with 0.3166, and Supplier 4 (S4) with 0.00019. This rating covers all specified criteria and sub-criteria, providing a basis for companies to select suppliers with the best performance and meet economic, environmental and social sustainability principles.

This work has some limitations as well. While 11 key criteria for sustainable supplier selection in the supply chain have been identified and ranked, other potential criteria and dimensions remain unexplored. Evaluating Sustainable Supplier Selection (SSS) criteria and identifying the most efficient sustainable supplier among alternatives were conducted using a framework based on FAHP and TOPSIS. The computations relied on expert input, underscoring the importance of performing these calculations meticulously.

For future research, alternative techniques and MCDM tools, such as ISM, TISM, and DEMATEL, could be employed to analyze the interrelationships and strengths of relationships among SSS criteria within the supply chain. Addionally, methods like PROMETHEE could be applied for supplier selection with a focus on sustainability, allowing for comparisons with the results of this study. Finally, an Interpretive Ranking Process (IRP) could be utized to rank SSS evaluation criteria about performance measures within supply chains.

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