International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 3,2025
https://www.theaspd.com/ijes.php

An Integrated Fuzzy Multi-Criteria Approach For Evaluating Sustainable Suppliers In Supply Chains: AHP, TOPSIS, And VIKOR

Jerin Joseph[1] , Rajeshwar S Kadadevaramath[2] , B.Latha Shankar[3] , Shiou-Yu Chen[4] , Akarsha Kadadevaramath[5]
[1]Research Scholar, Industrial Engineering & Management ,Siddaganga Institute of Technology ,Tumkur , Visvesvaraya Technological University,Belgaum, Karnataka, India
[2]Dean Academics, Amruta Institute of Engineering and Management Sciences , Bidadi, Karnataka, India ,
[3]Asso. Professor , Industrial Engineering & Management ,Siddaganga Institute of Technology ,Tumkur Karnataka, India
[4]Professor, National Taiwan Ocean University/ Keelung City, Taiwan
[5]Mechanical Engineer, Intel India Pvt. Ltd Bangalore, Karnataka, India
Corresponding auuthor: jerinjosephjj@gmail.com

Abstract
In today's rapidly changing regulatory landscape, with stricter environmental laws and increasing corporate pressures to adopt sustainable practices, companies must bolster their capabilities in implementing GSCM activities. This pressing need drives organizations to seek robust tools for evaluating and selecting eco-friendly suppliers. One promising approach is the use of Multi-Criteria Decision-Making (MCDM) methods, which enable comprehensive assessment and ranking of potential providers based on multiple relevant factors. To this end, the study introduces two advanced fuzzy-based decision-making techniques—fuzzy TOPSIS, fuzzy AHP and fuzzy VIKOR—designed to enhance supplier selection processes within green supply chain networks. These innovative methods provide a nuanced and flexible framework that captures uncertainties and subjectivities inherent in real-world decision environments, ultimately helping organizations make more informed, sustainable choices.
Keywords: *Supply Chain, Sustaibnability, MCDM, AHP,TOPSIS, VIKOR, Fuzzy*

INTRODUCTION

Supply Chain Network Design (SCND) refers to the development of a complex network of interactions between companies to control the flow of goods, information, and financial transactions. In the early 1990s, the primary focus of SCND was to maximize overall profits and/or reduce costs by optimizing the flow of materials through the supply chain. However, with shifting consumer preferences towards more sustainable products, growing regulatory pressures from governments and NGOs, and other influencing factors, companies are now placing greater emphasis on designing supply chains that prioritize sustainability. Supply chain managers view sustainability as a key factor in enhancing overall business performance, considering it within the context of economic, environmental, and social standards. In essence, managers aim to meet social and environmental expectations while adhering to public opinion, regulatory demands, and the economic needs of each manufacturing entity. The concept of the triple bottom line, which integrates economic, environmental, and social considerations, has emerged as a result of these factors, leading to the development of Sustainable Supply Chain Management (SSCM) theory and its application to business relationships and supply chains.

A company's sustainability success is heavily impacted by its suppliers, who form the first level of the supply chain. As a result, businesses must assess their suppliers for potential long-term partnerships. One of the key strategies in Sustainable Supply Chain Management (SSCM) is selecting suppliers based on sustainability criteria. By choosing the right suppliers, managers can secure the ideal raw materials at the right time, in the right quantity, and with the right quality. It's safe to say that the process of selecting and evaluating sustainable suppliers plays a crucial role in SSCM across various industries. In Supply

Chain Management (SCM), supplier selection is vital since businesses typically allocate at least 60% of their sales revenue to purchasing items like parts, components, and raw materials. Manufacturers can even spend up to 70% of a product's total cost on services and materials. To achieve effective SCM, supplier selection must be treated as a strategic, tactical consideration. In the 1990s, manufacturers began forming strategic alliances to boost management preferences and enhance their competitiveness. Supplier selection and evaluation have always presented complex challenges for decision-makers, as they must consider a wide range of factors. In today's competitive landscape, businesses are not only contending with each other but also striving to optimize and outperform rival supply chains. To adapt effectively to the dynamics of the global economy, companies must shift from a purely competitive mindset to one that emphasizes collaboration. Supply Chain Management (SCM) embodies a strategy that blends cooperation with competition, aiming to enhance operational efficiency and promote a more systematic, rational, and scientific approach to production management.

This study employs the entropy method to assign weights to various indicators and resolves conflicts between them using the VIKOR method alongside fuzzy Multi-Attribute Decision Making (MADM) techniques such as TOPSIS with fuzzy sets. These methods also facilitate the ranking of potential alternatives. The VIKOR method, in particular, enables decision-makers to reach a compromise solution that maximizes collective benefit while minimizing individual dissatisfaction. Based on the ideal point concept, VIKOR operates with a straightforward logic and fewer computational requirements. VIKOR proves especially valuable in multifaceted decision-making scenarios where decision-makers may lack the clarity or ability to express their preferences during the early stages of supplier selection. By enhancing group utility and reducing the regret of the less-favored option, compromise solutions generated through VIKOR can act as a foundation for negotiation and reflect the weighted preferences of decision-makers. Selecting the right technique requires aligning it with the specific nature of the problem. It is crucial to establish validation procedures and assess the practical applicability of the chosen approach. Before implementation in real-world scenarios, methods must undergo both conceptual and empirical validation. Researchers should aim to create a framework for method selection that is both theoretically robust and practically viable for solving real-life challenges.

LITERATURE REVIEW

The Analytic Hierarchy Process (AHP) is frequently applied in the context of Green Supply Chain Management (GSCM) due to its user-friendly structure and transparency. It is commonly used for evaluating and selecting suppliers, often employed independently to compare alternative options (Ireneusz Miciuła, 2018; G. Karunakumar, 2018). Nonetheless, a substantial portion of the literature highlights the integration of AHP with other decision-making methodologies to enhance the robustness of evaluations. These include methods such as ELECTRE III (Ali Alazzawi, 2020), VIKOR (Ashwani Kumar, 2019), PROMETHEE (Tsui & Wen, 2015), TOPSIS (Rajnish Kumar, 2018; Hsiu Mei, 2016; Yazdani, 2014; White, Wang & Li, 2015), and ARAS (Yan Kai-Fu, 2019; Jolanta Tamošaitienė, 2017). Additionally, AHP is sometimes combined with fuzzy number theory to better manage uncertainty and imprecision in decision-making scenarios (Yan Kai-Fu, 2019; Gülçin Büyüközkan, 2017; Ashwani Kumar, 2019). Other hybrid applications involve pairing AHP with the Taguchi loss function (Ashwani Kumar, 2019) or Goal Programming (Yan Kai-Fu, 2019). While supplier selection and evaluation remain the primary areas of AHP application within GSCM, it is also utilized for assessing green performance and conducting risk analysis.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a decision-making method designed to identify the best alternative that is closest to the ideal solution and furthest from the worst-case scenario within a multidimensional space. It offers several advantages, such as being easy to implement and program. However, one limitation is that it relies on Euclidean distance without considering the interdependence between criteria, which can complicate the evaluation when dealing with a large number of attributes and maintaining consistent judgments. The fundamental concept behind TOPSIS is that the most desirable option should have the shortest distance from the positive ideal solution and the greatest distance from the negative ideal solution (Kuo et al., 2015). Due to its ability to manage trade-offs among diverse criteria and accommodate numerous performance metrics, TOPSIS has become a popular tool for addressing supplier selection issues in supply chain management (Devika et al., 2013; Fallahpour, 2017).

In many cases, TOPSIS is integrated with other multi-criteria decision-making (MCDM) methods such as AHP (Analytic Hierarchy Process) or ANP (Analytic Network Process) to enhance the evaluation process (Wang, 2016; Yazdani, 2014; Li, 2015; Uygun & Dede, 2016; Ifçi, 2012a; Kuo et al., 2015). Its adaptability has also made it a widely used approach in addressing Green Supply Chain Management (GSCM) challenges under fuzzy environments (Kilic et al., 2020; Mohammed, 2019; Li & Wu, 2015; Sousa et al., 2014; Shen et al., 2013). TOPSIS, like AHP and ANP, is commonly employed in GSCM for supplier evaluation and selection, as well as for performance measurement and implementation planning.

VIKOR, introduced by Opricovic in 2004, was developed to assist decision-makers in reaching a final decision, generate compromise solutions under conflicting criteria, and facilitate the ranking and selection of alternatives (Hsu et al., 2013). As a more recent addition to the suite of Multi-Criteria Decision-Making (MCDM) tools, VIKOR stands apart from more established methods. It has been employed alongside approaches such as the fuzzy Best-Worst Method (BWM) to support supplier selection decisions (Kannan, 2020; Wu, 2019). Additionally, VIKOR has been integrated with other MCDM techniques like the Analytical Network Process (ANP) to enable the identification of sustainable and environmentally conscious suppliers (Valipour, 2017; Akman, 2015). VIKOR offers several advantages compared to other decision-making frameworks. Unlike TOPSIS, which focuses solely on the proximity to ideal and anti-ideal solutions, VIKOR incorporates both the maximization of group utility and the minimization of individual regret. This dual focus allows it to better align with the decision-makers' subjective preferences. Its primary applications lie in supplier assessment and selection, particularly in scenarios involving green supply chain practices. VIKOR is also frequently used to assess the effectiveness of green initiatives and the performance of environmentally responsible suppliers.

RESEARCH PROBLEM AND OBJECTIVES

This study evaluates sustainable suppliers by incorporating Green Supply Chain Management (GSCM) criteria alongside traditional economic factors. The main goal is to introduce multiple multi-criteria decision-making (MCDM) methods to identify the most suitable supplier within the manufacturing sector. The process begins with a comprehensive literature review to identify the critical criteria and influencing factors for supplier selection. In the next phase, procurement experts assess suppliers using a set of main and sub-criteria through the fuzzy Analytic Hierarchy Process (AHP). Subsequently, green suppliers are ranked and evaluated using two fuzzy-based techniques: fuzzy TOPSIS and fuzzy VIKOR.

RESEARCH METHODOLOGY

Research methodology for different Fuzzy MCDM used in this study are mentioned below,

4.1.Fuzzy AHP

Step 1: Define the problem and hierarchy – Set the goal, criteria, and alternatives.

Step 2: Make pairwise comparisons – Use linguistic terms, then convert them to fuzzy numbers.

Step 3: Calculate fuzzy weights – Apply a method like extent analysis or geometric mean.

Step 4: Defuzzify weights – Convert fuzzy numbers to crisp values (e.g., centroid method).

Step 5: Normalize weights – Ensure total weights sum to 1.

Step 6: Rank alternatives – Compute final scores and rank based on total weighted values.

4.2.Fuzzy TOPSIS

Step 1: Create decision matrix

Within that research, 5 factors and five alternatives are ranked using the fuzzy TOPSIS method. Every criterion's type and weight are displayed in the table below.

Step 2: Creating the Normalized Decision Matrix(NDM)

Using the Positive and Negative Ideal Solution (PIS and NIS) as a base, link the following to create a normalized choice matrix:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \quad ; \quad c_j^* = max_i \, c_{ij} \text{ ; } PIS$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \quad ; \quad a_j^- = min_i \, a_{ij} \text{ ; } NIS$$

Step 3:Creating the Weighted Normalized Decision Matrix(WNDM)

The WNDM, which took the changing weights of each criterion into account, is produced by multiplying each criterion's weight in the fuzzy NDM.

$$\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_{ij}$$

here $\tilde{w}_{ij}$ denotes the weight of the criterion c_j.

Step 4: Analyse the fuzzy positive ideal solutions (FPIS, A*) and the fuzzy negative ideal solutions ($\boldsymbol{FNIS, A^-}$)

The FPIS and FNIS of the alternatives are known according to the following criteria:

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*\} = \left\{\left(\max_j v_{ij} \,|i \in B\right), \left(\min_j v_{ij} \,|i \in C\right)\right\}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-\} = \left\{\left(\min_j v_{ij} \,|i \in B\right), \left(\max_j v_{ij} \,|i \in C\right)\right\}$$

here $\tilde{v}_i^*$ represents maximum value of i for all the alternatives and $\tilde{v}_1^-$ denotes minimum value of i for all the alternatives. *B* and C denote the PIS and NIS, resp.

The table below displays both the PIS & NIS.

Step 5: Analyze the distance between each alternative and the Fuzzy Positive Ideal Solutions(FPIS) $\boldsymbol{A^*}$and the distance between each alternative and the Fuzzy Negative Ideal Solutions(FNIS) $\boldsymbol{A^-}$

The following equations create the distances between each alternative and the FPIS and FNIS, respectively:

$$S_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*) \quad (\textit{ i range from 1 to m})$$

$$S_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad (\textit{ i range from 1 to m})$$

d is the distance between 2 fuzzy numbers when given 2 triangular fuzzy numbers (a_1, b_1, c_1) and (a_2, b_2, c_2), e distance between the 2 can be computed as follows:

$$d_v(\widetilde{M}_1, \widetilde{M}_2) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]}$$

Note that $d(\tilde{v}_{ij}, \tilde{v}_j^*)$ and $d(\tilde{v}_{ij}, \tilde{v}_j^-)$ are crisp numbers.

Step 6: Compute the closeness coefficient and rank the alternatives

The following formula can be used to determine each alternative's proximity coefficient:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

The greatest option is situated away from the FNIS and FPIS. The table below displays each alternative's proximity coefficient along with its ranking order.

4.3. Fuzzy VIKOR

Step 1: Create a decision matrix

The Fuzzy VIKOR technique is used in this research to rank five factors and five alternatives. The tables shown below gives the category of each factor and the weight .

After the alternatives have been evaluated in light of several factors, the decision matrix's conclusions are generated. Take note if there are several specialists involved in the evaluation because the matrix below displays the arithmetic mean of all specialists.

Step 2: Determining the positive ideal solution(PIS) and negative ideal solution(NIS)

There are both positive and negative ideal answers for each criterion, and they are as follows.

PIS (f̃^*) and NIS ((f)̃^°) can be found using the following relations if the criterion is positive:

$\tilde{f}_j^* = \underset{i}{Max}\, \tilde{f}_{ij}$ (here i ranges from 1 to n)

$\tilde{f}_j^\circ = \underset{i}{Min}\, \tilde{f}_{ij}$ (here i ranges from 1 to n)

If the criterion is negative, the relations given below can be used to get the PIS (f̃^*) and NIS ((f)̃^°):

$\tilde{f}_j^* = \underset{i}{Min}\, \tilde{f}_{ij}$ (here i ranges from 1 to n)

$\tilde{f}_j^\circ = \underset{i}{Max}\, \tilde{f}_{ij}$ (here i ranges from 1 to n)

Step 3: Generate the NDM

A normalizing choice matrix can be made by connecting the following, and using PIS and NIS as a base:

$\tilde{d}_{ij} = (\tilde{f}_j^* \ominus \tilde{f}_{ij})/(r_j^* - l_j^\circ)$ Positive ideal solution

$\tilde{d}_{ij} = (\tilde{f}_{ij} \ominus \tilde{f}_j^*)/(r_j^\circ - l_j^*)$ Negative ideal solution

Where

$\tilde{f}_j^* = (l_j^*, m_j^*, r_j^*)$

$\tilde{f}_j^\circ = (l_j^\circ, m_j^\circ, r_j^\circ)$

The table below displays the assessment matrix's normalized values.

Step 4: Compute the values $\tilde{S}_i$and $\tilde{R}_i$:

The values S̃ i and R̃ i can be derived as follows once the matrix has been normalized to form the weighted normalized decision matrix:

If $\tilde{R}_i = (R_i^l, R_i^m, R_i^r)$ and $\tilde{s}_i = (s_i^l, s_i^m, s_i^r)$

$$\tilde{S}_i = \sum_{j=1}^{J} (\widetilde{w}_j \otimes \tilde{d}_{ij})$$

$$\tilde{R}_i = \max_j (\widetilde{w}_j \otimes \tilde{d}_{ij})$$

Step 5: Compute the VIKOR index (Q)

The formula below can be used to determine Q's value.

If $\tilde{Q}_i = (Q_i^l, Q_i^m, Q_i^r)$

$$\widetilde{Q}_i = v \frac{(\tilde{s}_i \ominus \tilde{s}^*)}{s^{\circ r} - s^{*l}} \oplus (1 - v) \frac{(\tilde{R}_i \ominus \tilde{R}^*)}{R^{\circ r} - R^{*l}}$$

Where,
$\tilde{s}^* = \min_i \tilde{s}_i$
$s^{\circ r} = \max_i \; s_i^r$
$\tilde{R}^* = \min_i \tilde{R}_i$
$R^{\circ r} = \max_i \; R_i^r$
The variable v (indicating the highest group utility) will be assigned as 0.5 in this research. The following formula can be used to convert the hazy numbers S, R, and Q into distinct numbers.

If $\tilde{A} = (\mathrm{l}, \mathrm{m}, \mathrm{r})$ ($\tilde{A}$ is expressed as a fuzzy number)

$$Crisp(\tilde{A}) = \frac{2m + l + r}{4}$$

Step 6: Offering a compromise solution

Therefore, a choice is determined by the values of R, S, and Q, which are stated in descending order, for the alternatives. A selection of compromise answers can be suggested after the two choices that need to be made.
1st Condition. Acceptable advantage: $Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(m-1)$ where $A^{(1)}$ is the alternatives that are ranked Ist and $A^{(2)}$ is the alternative that is ranked 2nd in Q's ranking list. m is the no. of alternatives.

2nd Condition. Acceptable stability in decision making: Additionally, S or/and R must rank the alternative $A^{(1)}$ as the highest.

The following list of compromise solutions is suggested if any of the conditions are not encountered:
1st **Solution.** Alternatives $A^{(1)}, A^{(2)}, \ldots., A^{(M)}$ if condition 1 is not satisfied; Alternative $A^{(M)}$ is determined by $Q(A^{(M)}) - Q(A^{(1)}) < 1/(m-1)$ for max M (the positions of these alternatives are in closeness).

2nd **Solution.** Alternatives $A^{(1)}$ and $A^{(2)}$ if only 2nd condition is not satisfied.

3rd **Solution.** The alternative with the lowest Q value will be picked as the best one if all requirements are satisfied.

5. Case study and illustration

In a case study, five distinct suppliers were evaluated based on predefined green dimensions and associated criteria to validate the proposed performance evaluation method for Green Supply Chain Management (GSCM). The recommended model follow the fuzzy TOPSIS and fuzzy VIKOR approaches to analyze and rank the alternative suppliers. To select a supplier from a cohort of five equally qualified candidates (S1, S2, S3, S4, and S5), a decision-making committee comprising three experts (DM1, DM2, and DM3) was established.

Table 1 shows the fuzzy scale for AHP. Table 2 presents the economic and environmental criteria, along with the corresponding fuzzy weights assigned to each, which are to be considered during the supplier assessment. Tables 3 and 8 enumerate the fuzzy scales utilized in the TOPSIS and VIKOR algorithms applied in this study. Table 6 indicates the separation measures between the positive and negative ideal solutions with respect to economic and environmental factors. Table 7 illustrates the fuzzy TOPSIS results, including the ranking of each supplier and their closeness coefficients. Considering both economic and environmental criteria, Supplier 3 achieved the highest ranking. Furthermore, Tables 13 and 14 provide the crisp values of S, R, Q, and the ranking of alternatives derived from the fuzzy VIKOR approach for both economic and environmental factors. According to the fuzzy VIKOR method, Supplier 1 attained the highest ranking based on economic criteria, whereas Supplier 3 was ranked highest with respect to environmental (green) criteria.

Table 1 Fuzzy Scale for AHP

Code	Linguistic terms	L	M	U
1	Equal	1	1	1
2	Weak	0.5	1	1.5
3	Fairly strong	1.5	2	2.5
4	Very strong	2.5	3	3.5
5	Absolute	3.5	4	4.5

Table 2 Characteristics of Criteria and corresponding Fuzzy AHP weight

	Economic Factors	Green factors	Fuzzy weight
1	Quality	Green design	(0.200,0.250,0.300)
2	Lead time	Green image	(0.100,0.150,0.200)
3	Price	Green transformation	(0.250,0.300,0.350)
4	Productivity	Green logistics	(0.200,0.250,0.300)
5	Technology	Green Management System	(0.200,0.250,0.300)

Table 3 Fuzzy Scale for TOPSIS

Code	Linguistic terms	L	M	U
1	Very low	1	1	3
2	Low	1	3	5
3	Medium	3	5	7
4	High	5	7	9
5	Very high	7	9	9

Table 4 Normalised Decision Matrix (Economic criteria)

Supplier	Quality	Lead time	Price	Productivity	Technology
1	(0.556,0.778,1.000)	(0.429,0.600,1.000)	(0.429,0.600,1.000)	(0.556,0.778,1.000)	(0.556,0.778,1.000)
2	(0.333,0.556,0.778)	(0.333,0.429,0.600)	(0.333,0.429,0.600)	(0.333,0.556,0.778)	(0.556,0.778,1.000)
3	(0.778,1.000,1.000)	(0.429,0.600,1.000)	(0.333,0.429,0.600)	(0.778,1.000,1.000)	(0.333,0.556,0.778)
4	(0.333,0.556,0.778)	(0.429,0.600,1.000)	(0.333,0.429,0.600)	(0.333,0.556,0.778)	(0.556,0.778,1.000)
5	(0.111,0.333,0.556)	(0.429,0.600,1.000)	(0.429,0.600,1.000)	(0.556,0.778,1.000)	(0.333,0.556,0.778)

Table 5 Normalised Decision Matrix (Green criteria)

supplier	Green design	Green image	Green transformation	Green logistics	Green Management System
1	(0.556,0.778,1.000)	(0.333,0.556,0.778)	(0.778,1.000,1.000)	(0.556,0.778,1.000)	(0.556,0.778,1.000)
2	(0.333,0.556,0.778)	(0.556,0.778,1.000)	(0.556,0.778,1.000)	(0.778,1.000,1.000)	(0.556,0.778,1.000)
3	(0.556,0.778,1.000)	(0.333,0.556,0.778)	(0.556,0.778,1.000)	(0.778,1.000,1.000)	(0.556,0.778,1.000)
4	(0.333,0.556,0.778)	(0.333,0.556,0.778)	(0.556,0.778,1.000)	(0.556,0.778,1.000)	(0.556,0.778,1.000)
5	(0.333,0.556,0.778)	(0.333,0.556,0.778)	(0.333,0.556,0.778)	(0.556,0.778,1.000)	(0.333,0.556,0.778)

Table 6 Distance from PIS and NIS

Supplier	Distance from positive ideal (Economic)	Distance from negative ideal (Economic)	Distance from positive ideal (Green)	Distance from negative ideal (Green)
1	0.218	0.225	0.085	0.222
2	0.181	0.249	0.106	0.208
3	0.105	0.323	0.085	0.23
4	0.23	0.2	0.191	0.124
5	0.379	0.056	0.307	0.001

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 3,2025
https://www.theaspd.com/ijes.php

Table 7 Closeness coefficient

Supplier	Ci (economic)	Rank (Economic)	Ci (Green)	Rank (Green)
1	0.508	3	0.724	2
2	0.578	2	0.662	3
3	0.755	1	0.731	1
4	0.465	4	0.393	4
5	0.129	5	0.001	5

Table 8 Fuzzy scale for VIKOR

Code	Linguistic terms	L	M	U
1	Very Low	0	0	0.25
2	Low	0	0.25	0.5
3	Medium	0.25	0.5	0.75
4	High	0.5	0.75	1
5	Very High	0.75	1	1

Table 9 Normalised decision matrix (Economic criteria)

	Quality	Lead time	Price	Productivity	Technology
Supplier 1	(0.250,0.250,0.500)	(0.667,0.000,0.667)	(0.667,0.000,0.667)	(0.333,0.333,0.667)	(0.667,0.000,0.667)
Supplier 2	(0.000,0.500,0.750)	(0.333,0.333,1.000)	(0.333,0.333,1.000)	(0.000,0.667,1.000)	(0.667,0.000,0.667)
Supplier 3	(0.250,0.000,0.250)	(0.667,0.000,0.667)	(0.333,0.333,1.000)	(0.333,0.000,0.333)	(0.333,0.333,1.000)
Supplier 4	(0.000,0.500,0.750)	(0.667,0.000,0.667)	(0.333,0.333,1.000)	(0.000,0.667,1.000)	(0.667,0.000,0.667)
Supplier 5	(0.250,0.750,1.000)	(0.667,0.000,0.667)	(0.667,0.000,0.667)	(0.333,0.333,0.667)	(0.333,0.333,1.000)

Table 10 Normalised decision matrix (Green criteria)

Supplier	Green design	Green image	Green transformation	Green logistics	Green Management System
Supplier 1	(0.667,0.000,0.667)	(0.333,0.333,1.000)	(0.333,0.000,0.333)	(0.500,0.500,1.000)	(0.667,0.000,0.667)
Supplier 2	(0.333,0.333,1.000)	(0.667,0.000,0.667)	(0.333,0.333,0.667)	(0.500,0.000,0.500)	(0.667,0.000,0.667)
Supplier 3	(0.667,0.000,0.667)	(0.333,0.333,1.000)	(0.333,0.333,0.667)	(0.500,0.000,0.500)	(0.667,0.000,0.667)
Supplier 4	(0.333,0.333,1.000)	(0.333,0.333,1.000)	(0.333,0.333,0.667)	(0.500,0.500,1.000)	(0.667,0.000,0.667)
Supplier 5	(0.333,0.333,1.000)	(0.333,0.333,1.000)	(0.000,0.667,1.000)	(0.500,0.500,1.000)	(0.333,0.333,1.000)

Table 11 Fuzzy values of R, S and Q

Economic	Fuzzy R	Fuzzy S	Fuzzy Q
Supplier- 1	(0.050,0.083,0.233)	(0.483,0.146,0.917)	(0.752,0.000,0.752)
Supplier- 2	(0.000,0.167,0.350)	(0.250,0.442,1.275)	(0.623,0.188,1.000)
Supplier- 3	(0.050,0.100,0.350)	(0.333,0.183,0.958)	(0.710,0.031,0.910)
Supplier -4	(0.000,0.167,0.350)	(0.283,0.392,1.208)	(0.633,0.174,0.981)
Supplier -5	(0.050,0.188,0.300)	(0.317,0.354,1.167)	(0.580,0.189,0.907)

Table 12 Fuzzy values of R, S and Q

Green	Fuzzy R	Fuzzy S	Fuzzy Q
Supplier- 1	(0.033,0.150,0.350)	(0.508,0.200,1.067)	(0.698,0.072,0.892)
Supplier- 2	(0.067,0.100,0.300)	(0.475,0.183,1.042)	(0.729,0.008,0.826)
Supplier -3	(0.033,0.100,0.233)	(0.508,0.150,1.008)	(0.698,0.000,0.738)
Supplier -4	(0.033,0.150,0.350)	(0.442,0.383,1.283)	(0.681,0.118,0.946)
Supplier -5	(0.000,0.200,0.350)	(0.292,0.567,1.500)	(0.604,0.224,1.000)

Table 13 The crisp values S, R, Q and alternatives ranking (Economic)

Supplier	Crisp value of R	Rank in R	Crisp value of S	Rank in S	Crisp value of Q	Rank in Q
1	0.088	1	0.181	1	0	1
2	0.171	3	0.477	5	0.188	5
3	0.125	2	0.248	2	0.066	2
4	0.171	3	0.427	4	0.174	3
5	0.181	4	0.39	3	0.176	4

Table 14 The crisp values S, R, Q and alternatives ranking (Green)

Supplier	Crisp value of R	Rank in R	Crisp value of S	Rank in S	Crisp value of Q	Rank in Q
1	0.154	3	0.24	3	0.085	3
2	0.108	2	0.233	2	0.028	2
3	0.100	1	0.2	1	0.01	1
4	0.154	3	0.402	4	0.125	4
5	0.188	4	0.585	5	0.211	5

CONCLUSION

In conclusion, the integration of fuzzy multi-criteria decision-making methods, such as Fuzzy AHP, Fuzzy TOPSIS, and Fuzzy VIKOR, offers a comprehensive and effective framework for evaluating sustainable suppliers within complex supply chain environments. These methods address the inherent uncertainty and subjectivity in supplier selection by incorporating linguistic assessments and fuzzy logic. The increasing attention to sustainability and circular economy principles highlights the importance of selecting suppliers that align with environmental, economic, and social goals. As demonstrated in recent studies, the hybrid application of these techniques enhances decision accuracy and supports organizations in achieving long-term sustainability objectives within their supply networks.

References

Behrouz Alavi, Madjid Tavana, Hassan Mina, (2021), A Dynamic Decision Support System for Sustainable Supplier Selection in Circular Economy, *Sustainable Production and Consumption*, Volume 27, July 2021, Pages 905-920

Hassan Mina, Devika Kannan' Seyed Mohammad Gholami-Zanjani, Mehdi Biuki,(2021), Transition towards circular supplier selection in petrochemical industry: A hybrid approach to achieve sustainable development goals, *Journal of Cleaner Production*, Volume 286, 1 March 2021, 125273

Arash Khalili Nasr Madjid Tavana Behrouz Alavi Hassan Mina, (2021), A novel fuzzy multi-objective circular supplier selection and order allocation model for sustainable closed-loop supply chains, *Journal of Cleaner Production,* Volume 287, 10 March 2021, 124994

Devika Kannan Hassan Mina Saeede Nosrati-Abarghooee Ghasem Khosrojerdi, (2020), Sustainable circular supplier selection: A novel hybrid approach, *Science of the Total Environment*, Volume 722, 20 June 2020, 137936

Zhihua Chen, Xinguo Ming, Tongtong Zhou, Yuan Chang, (2020), Sustainable supplier selection for smart supply chain considering internal and external uncertainty: An integrated rough-fuzzy approach, *Applied Soft Computing*, Volume 87, February 2020, 106004

R.Krishankumar, Y.Gowtham, Ifjaz Ahmed, K.S.Ravichandran, Samarjit Kar, (2020), Solving green supplier selection problem using q-rung orthopair fuzzy-based decision framework with unknown weight information, *Applied Soft Computing*, Volume 94, September 2020, 106431

Sepehr Hendiani, Huchang Liao, Ruxue Ren Benjamin Lev, (2020), A likelihood-based multi-criteria sustainable supplier selection approach with complex preference information, *Information Sciences*, Volume 536, October 2020, Pages 135-155

Fatih Ecer Dragan Pamucar, (2020), Sustainable supplier selection: A novel integrated fuzzy best-worst method (F-BWM) and fuzzy CoCoSo with Bonferroni (CoCoSo'B) multi-criteria model, *Journal of Cleaner Production*, Volume 266, 1 September 2020, 121981

Mostafa Zandieha, BabakAslanib, (2019), A hybrid MCDM approach for order distribution in a multiple-supplier supply chain: A case study, *Journal of Industrial Information Integration,* Volume 16, December 2019, 100-104

M. Abdel-Baseta, Victor Changb, Abduallah Gamala, Florentin Smarandachec,(2019), An integrated neutrosophic ANP and VIKOR method for achieving sustainable supplier selection: A case study in importing field, *Computers in Industry,* 106 (2019) 94–110

Sanjay Kumar Saurabh KumarAsim Gopal Barman, (2018), Supplier selection using fuzzy TOPSIS multi-criteria model for a small scale steel manufacturing unit, *Procedia Computer Science,* Volume 133, 2018, Pages 905-912

Uygun, Ö & Dede, A. (2016, Performance evaluation of green supply chain management using integrated fuzzy multi-criteria decision-making techniques. *Computers & Industrial Engineering*. doi:10.1016/j.cie.2016.02.020