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Fuzzy TOPSIS Method for Sustainable Supplier Assortment in Green Supply Chain Management

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Abstract

INTRODUCTION: Green supply chain management (GSCM) represents one of the crucial ways for organizations to start minimizing their ecological footprint in the era of increasing ecological preoccupation and sustainability objectives. The critical issues of green supply chain management involve the assortment of green suppliers who are well-suited with the environmental objectives of organizations. Traditional supplier selection approaches often fail to address these uncertainties effectively. In this respect, the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution, shortly known as Fuzzy TOPSIS, is proposed for usage in this research for improving the process of supplier assortment in green supply chain management.
OBJECTIVES: The aim of this work is, therefore, to present an integrated framework, utilizing the Fuzzy TOPSIS method for selecting sustainable suppliers in green supply chain management. The particular aim of the study will be to incorporate environmental, social, as well as economic criteria in performance evaluation at the supplier level, by considering innate uncertainties and fuzziness related to sustainability metrics.
METHODS: The Fuzzy TOPSIS process is applied to assess and rank potential suppliers based on multiple criteria considering both environmental and economic factors.
RESULTS: Application of the Fuzzy TOPSIS method in sustainable supplier assortment demonstrates its effectiveness in identifying suppliers that align with green objectives while meeting operational requirements.
CONCLUSION: The proposed framework will provide a more fine-tuned and flexible tool for decision-makers by incorporating fuzzy logic into the complexities at hand for sustainability assessment. The findings underline the importance of adopting advanced techniques in decision making in order to attain environmental responsibility and long-term sustainability in supply chain operations.

Keywords: Fuzzy TOPSIS, Sustainable Supplier Selection, Green Supply Chain Management, MCDM, Fuzzy Logic, Sustainability Evaluation

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1. Introduction

In the view of increasing environmental concern and international awareness for sustainability, GSCM emerged as one of the crucial strategies for organizations to reduce their ecological footprint. Of all the GSCM practices, one of the key components is the selection of environmentally viable and sustainable suppliers-those who have similarities with environmental objectives and sustainability goals. However, existing supplier selection processes frequently find it difficult to account for the intricate interactions between social, economic, and environmental sustainability aspects, especially in ambiguous and imprecise situations.

Analytical Hierarchy Process (AHP) as well as Data Envelopment Analysis (DEA) are two examples of traditional decision-making techniques that are frequently deterministic and fall short of capturing the subjectivity and ambiguity present in sustainability criteria. Adopting sophisticated multi-criteria decision-making strategies that can manage uncertainty in supplier evaluation is necessary to close this gap. This paper discusses Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) as a method that can help in the process of supplier selection under GSCM [1-3].

These motives drove the research to focus on the development of an integrated framework, based on the Fuzzy TOPSIS method, for selecting sustainable suppliers in GSCM. Such a framework would cover the integration of environmental, social, and economic criteria for the assessment of suppliers while accounting for the inherent uncertainty and fuzziness in the metrics of sustainability. Fuzzy logic is included into the proposed framework in order to solve the shortcomings of conventional supplier selection techniques and offer a more accurate and flexible decision-making mechanism. Fuzzy TOPSIS is adopted for research purposes to find the grade of each supplier across multiple chosen criteria with respect to environmental and economic issues.

Fuzzy TOPSIS, with its high recognition in handling vagueness and imprecision, would be apt for this purpose. It allows for finer screening of suppliers, considering the attendant vagaries involved with such assessments of sustainability. The presentation of this process in the selection of sustainable suppliers shows that the identified suppliers are not only fitting for green objectives but also operational requirements [4, 5].

Results show the need to apply comprehensive decision-making methods, thereby developing environmentally responsible and sustainable supply chain operations. Fuzzy logic in the proposed framework with adaptive and integral tools supports the decision maker in getting through tangled aspects of the sustainability evaluation. It will help modern enterprise production management stability economic assistances as well as environmental sustainable development effectively.

As the literature explains, resource shortages and environmental pollution have become critical issues around the world, and only a supply chain management approach that aims at economic efficiency and ecological sustainability can satisfactorily address such important issues. The concept of SCM has been changing over the years since it was first proposed in the early 1980s and involves materials management, information flow, and a series of logistics activities within or across companies. It has also evolved over time to become information flow that is sophisticated, relationship networks, and governance of the supply network. GSCM cropped up in the late 20th century as a model that combines economic benefits along with environmental sustainability and thus gained a wide audience among research fields [6, 7]. It comprises many integral components, such as green product design, supplier assessment, manufacturing, packaging, transportation, marketing, and resource recovery. Green suppliers form one of the most advanced ends of supply; hence, they are also critical cost savers and environmental protectors, impacting all subsequent links in the chain. Indeed, the greening of selected suppliers will enhance the compatibility and ecological performance of the whole supply chain, making it core to GSCM [8-11].

For the selection of green suppliers, some of the environmental criteria existing studies pointed out include: environmental practices, hazardous substances management, and GSCM reputations of the company. Yet, after-sales service as a criterion in such scenarios is relatively unexplored. Decision-making problems in selecting green suppliers also need to consider linguistic uncertainties and incomplete information. Some of the different techniques proposed to provide these gains in decision reliability for uncertain environments include: the method of determination of weights based on negation of probability distribution and the determination of criterion weight using measures of similarity and aggregation operators [12-14].

Therefore, this paper contributes to the existing literature by embedding a framework of fuzzy logic within the GSCM supplier selection process. The Fuzzy TOPSIS method will address the problem of the complexity and uncertainty of the sustainability criteria and provide a more flexible and accurate tool to the decision-makers for sustainable and environmentally responsible supply chain management.

2. Related Works

The selection of environmentally friendly suppliers within GSCM has been a significant concern over recent years due to growing ecological concerns and the need for companies to start practicing sustainability. A number of researchers have proposed various types of models and methods to address complications related to multi-criteria decision-making in the context of supplier evaluation.

Zulqarnain et al. [15] propose an incomplete and imprecise data model for representing the decisions involved in selecting suppliers in a GSCM using q-rung orthopair fuzzy soft sets (q-ROFSS). Based on q-ROFSS, their method extends the traditional Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) by incorporating measures into the q-ROFSS framework to better handle MAGDM problems. The research work identified the utility of the model proposed for selecting suppliers based on various criteria including quality, reliability, and sustainability practices.

Wang Chen et al. [16] underlined that the economic as well as ecological criteria should be adopted during the green supplier assortment process. They proposed a comprehensive fuzzy MCDM approach by integrating fuzzy AHP concerning determination of the criteria weights in uncertain environments and fuzzy TOPSIS in order to rank potential suppliers. A real case study in the Luminance Enhancement Film industry showed its application in action and re-verified its efficiency and applicability in real-world cases.

Ghosh et al. [17] anticipated an combined MCDM approach for evaluating supplier organizations within the context of GSCM of Indian industrial sectors. In the weight determination process, a combination of entropy methods was used, while several MCDM techniques in ranking, namely complex proportional assessment as well as grey relational analysis, were applied for the ranking of suppliers. The study shed light on several significant parameters, like total energy consumption and utilization of renewable energy, of paramount importance for the assortment of a green supplier and pointed out that the manufacturing organizations could be used as benchmarks for other sectors.

Liou et al. [18] developed a combined MCDM model integrating support vector machines (SVM), the fuzzy best-worst method (FBWM), and fuzzy TOPSIS for identifying the most suitable green suppliers. In this model, SVMs were employed to derive key criteria from historical data, while the fuzzy best-worst method was used to assign weights to these criteria. This approach was applied in a case study involving a global electronics company, leading to a comprehensive ranking of green suppliers and providing crucial insights for decision-makers.

Kao et al. [19] explored a sustainable supplier selection strategy in the garment sector using a Fuzzy MCDM approach to aid decision-makers in situations of uncertainty. The study combined Fuzzy Analytic Hierarchy Process (FAHP) with Weighted Aggregated Sum Product Assessment (WASPAS) to identify the optimal supplier under fuzzy conditions. The model's practicality and effectiveness were demonstrated through an actual case study.

Shojaei et al. [20] focused on green supplier selection within the construction sector and incorporated rough set theory within an MCDM framework. This model identified fifteen relevant criteria, applying rough AHP to assign weights to the criteria and rough TOPSIS to rank the suppliers. The findings highlighted that environmental awareness and green social responsibility are key criteria in evaluating green suppliers, essential for sustainable development in the construction industry.

Quan et al. [21] designed a framework for assessing green suppliers using a combined approach that integrates multiple criteria decision-making (MCDM) techniques with interval-valued intuitionistic uncertain linguistic sets. They employed an ant colony optimization algorithm to group decision-makers into clusters and used the MULTIMOORA method to rank suppliers. The effectiveness of this framework was demonstrated through a practical example in the real estate industry, proving its applicability in decision-making scenarios that involve large groups.

Matić et al. [22] introduced a hybrid MCDM model for sustainable supplier selection, combining the FUCOM method for determining criterion weights with rough COPRAS for evaluating different alternatives. The model's reliability was verified through sensitivity analysis, which showed consistent supplier rankings, making it a valuable tool for decision-making in sustainable supply chain management.

Li et al. [23] proposed a new supplier selection model using the TODIM method within the context of cloud manufacturing. This model considers the diverse nature of evaluation information and incorporates the risk preferences of decision-makers. Its effectiveness was confirmed through a comprehensive approach that includes multiple attributes with different weightings, making it a robust framework for selecting green suppliers.

Liu et al. [24] developed an innovative MCDM model that integrates the Best-Worst Method (BWM) with the Aggregated Quality Measure (AQM) in an environment with interval-valued intuitionistic uncertain linguistic data. This model is effective in addressing uncertainties and ambiguities in decision-makers' judgments, providing reliable supplier rankings, as shown in a case study involving a watch manufacturing company.

In the general view, these studies introduce various approaches and methodologies applied to the field of sustainable supplier selection in GSCM, each of them adding a different perspective and set of tools to manage the complexity of GSCM decision-making under uncertainty. The integration of fuzzy logic, hybrid MCDM models, and advanced computational techniques denotes a rising trend toward more sophisticated and accurate models in green supply chain management.

Table 1 Comparative analysis of different related works

Authors	Methodology	Criteria Considered	Application Domain	Key Findings
Zulqarnain et al. [15]	q-ROFSS with TOPSIS	Quality, Reliability, Capacity, Compliance, Sustainability	Green Supply Chain Management (GSCM)	q-ROFSS extended TOPSIS for handling incomplete and ambiguous data effectively.
Wang Chen et al. [16]	Fuzzy AHP & Fuzzy TOPSIS	Economic (Cost, Quality, Lead Time), Environmental	Luminance Enhancement Film Industry	Proposed a comprehensive fuzzy MCDM for green supplier selection, emphasizing environmental criteria.

Ghosh et al. [17]	Entropy Method, Complex Proportional Assessment, Grey Relational Analysis	Energy Consumption, Scrap Material, Renewable Energy Utilization	Indian Industrial Sectors	Identified key sustainability parameters; manufacturing sector as a benchmark for others.
Liou et al. [18]	SVM, Fuzzy BWM, Fuzzy TOPSIS	Economic, Environmental	Multinational Electronics Manufacturer	Hybrid model combining data mining and MCDM for effective green supplier prioritization.
Kao et al. [19]	FAHP & WASPAS	Economic, Environmental	Garment Industry	Applied a Fuzzy MCDM approach to successfully select optimal suppliers in uncertain environments.
Shojaei et al. [20]	Rough AHP, Rough TOPSIS	Environmental Awareness, Green Social Responsibility	Construction Industry	Prioritized suppliers with emphasis on environmental and social responsibility in construction projects.
Quan et al. [21]	Interval-Valued Intuitionistic Uncertain Linguistic Sets, Ant Colony Algorithm, MULTIMOORA	Environmental, Economic, Social	Real Estate	Demonstrated practical utility in large group green supplier selection.
Matić et al. [22]	FUCOM, Rough COPRAS, Rough Dombi Aggregator	Economic, Environmental, Social	Construction Industry	Provided a highly consistent ranking of sustainable suppliers through a hybrid MCDM model.
Li et al. [23]	TODIM, Fuzzy BWM, Entropy Weights	Green Criteria, Risk Attitude	Cloud Manufacturing	Addressed multi-subject participation and risk attitudes in green supplier selection.
Liu et al. [24]	BWM, AQM with Interval-Valued Intuitionistic Uncertain Linguistic Sets	Economic, Environmental, Social	Watch Manufacturing	Developed a novel MCDM model capturing uncertainty and vagueness in decision-making.

Despite the genesis of the approaches for selecting sustainable suppliers, the development of an integrated model incorporating environmental, social, economic, technological, and after-sales service criteria into GSCM has been lagging behind. Although many previous works have focused on various aspects of the supplier selection problem, such as the application of fuzzy logic or hybrid MCDM approaches, most previous studies are more focused on economic and environmental criteria or are industry-sector-limited.

This research fills the identified gap by adopting the Fuzzy TOPSIS method to evaluate suppliers based on various criteria such as Environmental Practices, Social Responsibility, Economic Performance, Technological Capability, and After-Sales Service. The proposed model not only presents balanced judgment related to suppliers but also enhances the decision-making process by considering different criteria that have assumed crucial dimensions for sustainability in supply chain management. The findings from this present study contribute to the literature by providing a more holistic approach to the issue of sustainable supplier selection that can be applied across industries and addresses the emerging need for comprehensive frameworks concerning evaluation in GSCM.

3. Materials and Methods

The sequence of a structured approach followed for the selection of a sustainable supplier under GSCM is described in the section. The study starts with the identification of a holistic set of criteria that are necessary for screening a supplier in respect of sustainability. These criteria cover several dimensions associated with green supply chains, such as environmental, economic, social, technological, and other dimensions. Each of the selected criteria is chosen based on its relevance to the sustainability goals of the supply chain. This would then be followed by the consideration of multiple alternative suppliers against whom the criteria would be put to the test and thus yield a fair comparison of their standing, representative of real-world complexity [25-28].

In order to appraise these alternatives efficiently, their prioritization has to be done using the Fuzzy Technique for Order Preference by Similarity to Ideal Solution, hence called Fuzzy TOPSIS. This technique is suitable in handling intrinsic uncertainty and vagueness in human judgments and evaluations during a decision-making process. Fuzzy TOPSIS embraces fuzzy set theory for the inclusion of ambiguous information and uses a structured approach in order to estimate the closeness of each alternative to the ideal solution. Adopting this into the TOPSIS framework, as done in this work, makes the assessment of supplier sustainability performance nuanced and more accurate in supporting decision-makers on the choice of the most suitable suppliers for their green supply chains.

The intricacies and uncertainties involved in sustainable supplier selection are addressed in this work by using the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). Instead of using strict binary logic (true or false), fuzzy logic allows partial truth values between 0 and 1, making it a mathematical foundation for handling imprecise, unclear, and uncertain information. When making decisions, this method is especially helpful when linguistic variables (such as "high," "moderate," or "low") and subjective assessments are important considerations. Fuzzy TOPSIS models the inherent ambiguity in sustainability assessments by representing supplier selection criteria as fuzzy numbers.

The approach involves a number of important steps. First, the alternatives and decision criteria are determined in terms of environmental, social, and economic factors. Second, fuzzy linguistic words are employed to represent expert opinions on the supplier performance and importance of criteria. These words are transformed into triangular fuzzy numbers (TFNs) because they are widely applied in fuzzy logic since they are easy to use and effective in dealing with uncertainty. A TFN is characterized by three parameters: the minimum possible value (lower bound), the most probable value (middle), and the maximum possible value (upper bound), providing a flexible representation of subjective judgments. Then, the weighted fuzzy decision matrix is formed, and the fuzzy positive and negative ideal solutions are identified. Finally, the closeness coefficient is computed for ranking the suppliers according to their proximity to the ideal solution. This methodology improves the resilience of supplier selection in green supply chain management by using fuzzy logic. It enables decision-makers to better handle language uncertainties, increase evaluation accuracy, and create more accurate sustainability assessments.

3.1. Different Factors for the Evaluation

Environmental Practices (EP)

It is an important criterion in the selection of sustainable suppliers, and it reveals the supplier's concern with environmental care and obedience to the relevant regulations and standards. The evaluation of environmental practices mainly aims at analyzing a supplier's efforts to cut down on waste, reduce emissions, and improve energy efficiency. Commonly, those suppliers who are found to depict the best environmental practices usually adopt an integral waste management system wherein waste is minimized, recycled, or disposed of by environmentally friendly methods. Suppliers also do their best to reduce greenhouse gas emissions by optimizing routes and using fuel-efficient vehicles, among other ways, and are increasingly looking at switching to renewable energy sources.

Besides waste and emission management, energy efficiency is another important environmental practice. Many suppliers who are into sustainability invest in various energy-efficient technologies and processes that reduce the level of energy use, and hence carbon footprint emission. It may entail the use of energy-efficient machinery, putting in place smart energy management systems, or even infusing green building practices within the facilities.

Other than this, sustainable resource management is another essential component of this that addresses the focus of suppliers on responsible use and sustainability of the resources. It would involve raw material sourcing from environmentally friendly sources that are also ethically managed, reduction of water usage, and ensuring that materials are used in a way to minimize environmental impact.

Also, environmentally conscious suppliers tend to pursue and maintain such certifications as ISO 14001, which stipulates a framework of a decent environmental management system. Such certification documents a supplier commitment to continuous improvement in the field of environmental performance and consistency with high environmental standards.

That is, the development of suppliers' environmental practices means the development of the entire supply chain's environmental sustainability. Additionally, it enhances their reputation and competitiveness in the market. To organizations, choosing suppliers who possess good environmental practices are those whose supply chains complement the sustainability objectives of an organization in relation to long-term environmental concerns and global actions towards climate change.

Social Responsibility (SR)

The social responsibility parameter stands as one of the critical parameters of the sustainable supplier selection process and reflects the commitment of suppliers with regard to ethical practices, labor practices, and commitments to the community. While assessing the social responsibility of suppliers, verification should be undertaken in the sense that the code of conduct for fair labor practices has been implemented for ensuring a safe working environment, getting fair wages, and enjoying the rights of workers. Highly socially responsible suppliers will likely have policies and programs that enable employees to feel that their well-being is considered, through health and safety training, fair compensation, and allowing for professional development.

Besides labor practices, a commitment to human rights by a supplier is very significant. This includes the assurance of operations free from child labor, forced labor, and any type of discrimination. The suppliers whose standards in social responsibility are high are always up to contributing to practices that uphold human dignity and support equality and inclusion in the workplace.

Apart from that, community involvement is also one of the major parts of social responsibility. Those who have a sense of social responsibility within themselves normally engage in activities and projects that are for the benefit of the communities in which their business operations exist. This can include things like providing to local economic development, supporting education, and other charitable contributions. The investment by such suppliers in the social fabric of their communities fosters positive impacts reaching beyond their immediate business operations.

Additionally, many socially responsible suppliers go the extra mile to try and be in step with international guidelines and frameworks, such as the United Nations Global Compact and International Labour Organization conventions. In turn, such frameworks give direction on acceptable business behavior and social accountability that ensure the operation of suppliers in a socially responsible and ethically proper manner.

By strategically selecting a supply base comprising those suppliers who pay high attention to social responsibility, organizations will have their supply chains support broader societal goals and contribute to sustainable development. This indeed enhances the ethical standing of the supply chain but also helps in building up trust and loyalty among customers, employees, and stakeholders who increasingly value and support businesses that show a real commitment to social issues.

Economic Performance (EcP)

The ability of the performance based on economic criteria depends on the financial stability, cost-effectiveness, and general economic value that a supplier can offer. Economic performance appraisal of a supplier encompasses an analysis of a supplier's performance based on delivering competitively priced products or services with quality and reliability. Suppliers that portray excellent economic performance normally operate under very efficient operations and hence can provide very cost-effective solutions with no compromise on quality.

Economic performance of suppliers in an organizational setup differs regarding the financial stability of partners. The financially healthy business generally characterizes those suppliers who shall be reliable partners, able to maintain long-term relationships and adhere to all contractual obligations. Their reputation in the market, credit ratings, and financial statement reports usually maintain this stability. Such suppliers bring less risk to organizational exposure compared to other suppliers that may go bankrupt or go through financial distress and hence disrupt the chain.

In addition, a second important foundation of economic performance will be cost-effectiveness. Suppliers who can deliver products and services at a lower price, while maintaining specifications with respect to quality and sustainability, contribute significant economic value to the buying organization. It means much more than offering products at prices that are competitive but, instead, an efficient production process, economies of scale, and strategic sourcing of raw materials.

Besides, economic performance involves the supplier's ability to innovate and continuously improve. Those suppliers who are able to make significant research and development in their effort to improve products, adopt new technologies, and streamline operations contribute to the general economic strength of the supply chain. This often leads to innovative results in cost savings, higher quality products, and increased competitiveness in the market.

Other critical factors relate to value for money. This implies that the offerings from the supplier have to be well-balanced between costs and quality in ensuring that the buying organization achieves an optimum return on its investment. Most suppliers that exhibit superior economic performance normally demonstrate excellent insight into the dynamics of the market, customers, and pressures of the competitors to enable them to offer superior value propositions.

This means that within each selection, the economic performance of suppliers should be a priority to ensure supply chains are cost-efficient but also resilient enough to support long-term business growth. In this way, an appropriate balance between economic benefits and sustainability of the overall supply chain can be achieved.

Technological Capability (TC)

Technological capability is also one of the key selection criteria in the process of finding a sustainable supplier. This would denote the potential of a supplier to make full use of advanced technologies to sustain best practices and operational efficiency. In this regard, an assessment of technological capability could be centered on how suppliers invest in state-of-the-art technologies to support environmental sustainability, innovation, and process improvement.

Suppliers demonstrating good technological capability are competent in adopting green technologies that reduce environmental impact. Examples include energy-efficient technologies such as energy-efficient machinery, intelligent energy management systems, and renewable energy sources. Advanced technologies in the management of wastes, recycling processes, and reduction of emissions also mean a supplier is committed to environmental stewardship.

Besides environmental technologies, technological capability also includes innovation and product development. Suppliers investing in R&D to enhance their products by adding sustainable features and materials contribute to the overall sustainability of the supply chain. This may include the development of eco-friendly products, enhancement of product lifecycle management, and integration of sustainable design principles in their manufacturing processes.

Moreover, technological capability also encompasses digitalization and data-driven decision-making. Those suppliers that take advantage of digital technologies, such as Internet of Things devices, artificial intelligence, and big data analytics, can achieve better operations, increased supply chain visibility, and decreased resource consumption. These technologies enable real-time monitoring of environmental metrics, predictive maintenance of equipment, and agile response to market demands, leading to the improvement of supply chain efficiency and sustainability on a whole different level.

In addition, technological capability covers a supplier's preparedness for continuous change in technology and industrial standards. The more agile and flexible suppliers in adopting new technologies and adjusting to the ever-changing regulatory requirements are those who can better meet the emerging needs for sustainability and growing customer expectations.

This will ensure the supply chains are competitive, resilient, contribute to the organizational goals on sustainability, and are selected based on technological capability. This would definitely drive not only innovation and efficiency but also long-term environmental sustainability and operational excellence across the supply chain.

After-Sales Service (AS)

After-sales service refers to the competence of the supplier to offer support and assistance to customers after the product has been delivered. After-sales assessment will focus on the quality, responsiveness, and effectiveness of the post-purchase support system of the supplier.

Good after-sales service forms part of a supplier's follow-through that involves after-sales customer satisfaction and retention through timely, reliable support in operation. This would include installation, maintenance, and repair so that the product operates effectively over a longer period. Suppliers can also provide warranties, service agreements, and technical support hotlines to ensure timely handling of customer queries and problems.

Effective aftersales service also concerns ease of approachability and response. Those suppliers who do not allow their lines of communication to become clogged up, and who also maintain teams of customer service that are quick to respond, find their customers getting in touch with them without much hassle and securing timely solutions to their problems. The responsiveness helps build a sense of trust and loyalty among the customers, thereby amplifying their overall experience and satisfaction.

Besides that, it is support and training in operation that complete after-sales service. Some suppliers might offer customer and/or end-user training programs which would ensure the most efficient product operation by customers and thus guarantee safe operation. This proactive approach helps increase not only the competencies of the customers but also minimizes any chance of operational errors and downtimes.

Also, good after-sales service providers typically seek customers' feedback for the continuous enhancement of their support processes and prioritization of recurring problems. This would mean customer-centricity for continuous improvement and customer satisfaction, allowing the reputation of a supplier to be settled as a reliable partner in all aspects.

Organisations can reduce a number of risks by making after-sales service pivotal in their selection of a supplier. These may include product failure risk, operational efficiency, and overall supply chain reliability. A strong focus on after-sales support ensures long-term nourishment of customer relationships, strong brand loyalty, and differentiates suppliers in increasingly competitive markets where customer service excellence is highly valued.

3.2. Different Alternatives for the Evaluation

The subsequent step involves identifying various alternatives that will be evaluated. This process is essential for establishing the potential options available for analysis using the selected criteria.

Supplier A:

Supplier A exemplifies the firm commitment to the best environmental practices and observing stiff standards on sustainability. The concern of reducing waste, minimizing emissions, and developing better energy efficiency by Supplier A is very proactive in terms of environmental stewardship. It invests in emerging green technologies that go beyond mere regulatory compliances but set industry standards for sustainable manufacturing and operations. Supplier A has considerably reduced the environmental impact of its operations within the supply chain by incorporating the highest level of environmental management systems. This holistic commitment to sustainability not only aligns with current global environmental goals but also provides a lead position as a valued partner, one who can guarantee eco-friendly solutions that do not diminish in quality or efficiency.

Supplier B

Supplier B also represents high performance in terms of social responsibility, mainly through its very steadfast commitment to the concerns of ethical labor practice and community involvement. Because this supplier has had a reputation for conformity to standards related to fair labor, safe working conditions, adequate wages, and opportunities for professional development are assured and from which employees truly benefit. Further, the company involves itself in the community development projects, helping to grow local economies, as well as having positive social impacts. While supplier B is committed to human rights and social equity, going beyond the minimum legal compliances, incorporation of ethical practices in business operations with a motto of fostering a culture of inclusivity and social responsibility at the community level, by promoting ethical values and welfare at the community level, besides its reputation, is contributing positively towards the achievement of the Sustainable Development Goals in areas of operation.

Supplier C

Supplier C has the strongest economic performance, and its ability to deliver cost-effective solutions cannot be questioned. Thus, Supplier C can propose efficient value propositions against the clients' economic needs with its sound economic condition and competitive pricing strategies. The financial stability hence assures reliability in terms of quality regarding products and services offered by the company for gaining confidence of both customers and stakeholders. Supplier C can balance operational efficiencies and utilize economies of scale to assure competitive pricing without sacrificing product integrity or customer satisfaction. An emphasis on efficiency and cost-effectiveness will enable Supplier C to continue being a reliable selection for organizations whose supply priorities focus on economic sustainability and operational excellence.

Supplier D

Supplier D is at the forefront of technological capability, driven by the insatiable need for continuous innovation and a vision of sustainability. With worldwide acknowledgment for the adoption of advanced technologies, it leads the development of eco-friendly products and manufacturing processes that assure lessened environmental impact. The company's commitment to sustainable innovation has been proven through continuous investment in research and development to enhance product quality, its productivity, and environmental performance. Supplier D's other technological capabilities include smart manufacturing practices and integration of renewable sources of energy, thus highly contributing to carbon footprint reduction in all its operations. With a reputation for high-quality and innovative solutions, it has managed to set industry standards for technological excellence and support sustainable development goals. Choosing Supplier D will definitely guarantee one the latest in-use technologies and sustainable solutions, aligned to modern environmental and operational imperatives.

Supplier E

Supplier E is known for excelling in after-sales service, and thus, support and customer satisfaction are unparalleled. The products of Supplier E come with a wide range of maintenance, repair, and technical support services at excellent orientation toward post-purchase support, which further enhances the reliability and durability of the product. Their response team and efficient support lines can get issues resolved just as soon as they arise, hence significantly reducing losses due to operational downtime. Supplier E doesn't stop at reactive support; he even extends his care for customers to regular training programs and resources that make them self-sufficient in extracting full value from their products. With such strong emphasis on excellence in after-sales service, Suppliers E builds long-term trust, reliability, and a commitment to seamless experiences with the customer.

Supplier F

Supplier F is balanced on all environmental, social, and economic criteria; hence, it's versatile for sustainable supplier selection. The company has inculcated various environmental best practices into its operations that minimize ecological impact and ensure resource efficiency along the value chain of the company. Supplier F also shows a very strong commitment to social issues: ethical labor practices, community involvement, and inclusive business practices. This is economically priced by Supplier F and ensures value for money, hence cost-effective while one does not have to give up on any of the sustainability objectives. By adopting a holistic approach to sustainability, Supplier F contributes toward a wide range of societal and environmental objectives while meeting customer operational needs. Commitment to comprehensive sustainability or responsible business is what selection of Supplier F means, where it forms a worthy partner in achieving long-term sustainability objectives.

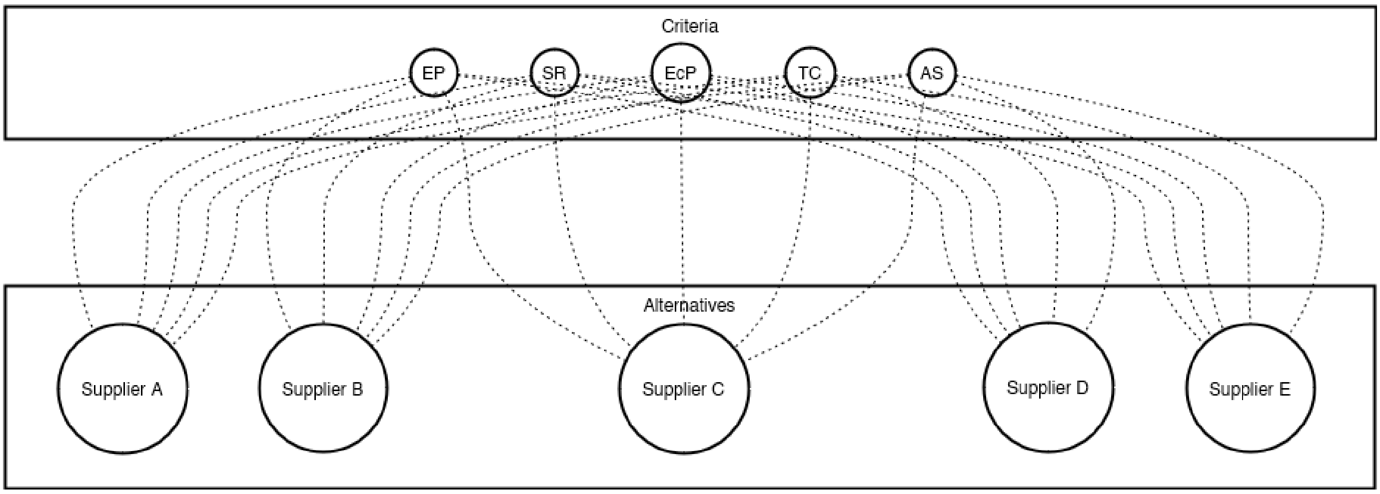

Figure 1. Hierarchical structure for the evaluation

4. Results

The following section presents the outcomes of applying the Fuzzy TOPSIS method with the aim of evaluating and ranking potential suppliers with respect to comprehensive criteria, including environmental practice, social responsibility, economic performance, technological capability, and after-sales service. This analysis will try to provide an insight into how each supplier contributes toward the achievement of sustainability objectives in a green supply chain management setting. In this context, using Fuzzy

TOPSIS, we try to put forward the relative strengths and efficiencies of each supplier so as to present an appropriate understanding with regard to their respective contributions toward sustainable supplier selection and its alignment with organizational sustainability goals [29-32].

Step 1: Develop a Decision Matrix

First, in this research, it constructs a decision matrix necessary for the assessment process by using Fuzzy TOPSIS. As a result, five different criteria and a total of six alternative suppliers were all put into this matrix, whereby every criterion has a certain weight according to its importance in the overall assessment. The decision matrix has been set up to systematically organize the criteria and their corresponding weights, thereby enabling a structured comparison between alternatives. This is necessary in order for a proper Fuzzy TOPSIS approach to be applied because it requires the detailed evaluation of the performance of each supplier against identified criteria [33, 34].

Table 2 Properties to define and distinguish each criterion

name	type	weight
EP	+	**(0.200,0.200,0.200)**
SR	+	**(0.200,0.200,0.200)**
EcP	+	**(0.200,0.200,0.200)**
TC	+	**(0.200,0.200,0.200)**
AS	+	**(0.200,0.200,0.200)**

The subsequent table illustrates the fuzzy scale utilized in the model.

Table 3 Representation the linguistic terms and their corresponding fuzzy numbers

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

The alternatives are weighed up against the criteria, and the results of the decision matrix are presented in the table below. Note that in the event that there were multiple experts involved in making the assessment, the matrix below represents the arithmetic average of their judgments [34-36].

Table 4 Alternatives evaluated against various criteria

	EP	SR	EcP	TC	AS
Supplier A	(4.600,6.600, 8.400)	(4.600,6.600, 8.200)	(3.400,5.200, 7.200)	(3.600,5.600, 7.600)	(3.400,5.400, 7.400)
Supplier B	(1.600,3.000, 5.000)	(1.800,3.600, 5.600)	(1.600,3.200, 5.200)	(1.600,2.800, 4.800)	(1.000,2.200, 4.200)
Supplier C	(3.800,5.800, 7.600)	(3.400,5.400, 7.200)	(2.200,4.200, 6.200)	(4.200,6.200, 8.200)	(2.000,4.000, 6.000)
Supplier D	(4.800,6.800, 8.600)	(6.200,8.200, 8.600)	(6.400,8.400, 8.800)	(5.600,7.600, 8.600)	(5.400,7.400, 8.800)
Supplier E	(2.600,4.600, 6.600)	(1.800,3.800, 5.800)	(2.400,4.400, 6.400)	(3.200,5.200, 7.200)	(2.400,4.200, 6.200)
Supplier F	(1.600,3.600, 5.600)	(1.800,3.400, 5.400)	(1.200,3.000, 5.000)	(2.200,3.600, 5.600)	(1.800,3.400, 5.400)

Step 2: Construct the Normalized Decision Matrix

It gives the normalized decision matrix from the positive and negative ideal solutions of the criteria. Normalization in this regard means adjustment of the matrix by the highest and lowest values of the alternatives with respect to each criterion. That is to say, for each criterion, its values will be normalized into a maximum value considering the positive ideal solution and also the minimum value reflecting the negative ideal solution for comparability. Thus, changed values are obtained and a normalized decision matrix is constructed. Values changed in the matrix are given in the following table.

Table 5 A normalized decision matrix

	EP	SR	EcP	TC	AS
Supplier A	(0.535,0.767, 0.977)	(0.535,0.767, 0.953)	(0.386,0.591, 0.818)	(0.419,0.651, 0.884)	(0.386,0.614, 0.841)
Supplier B	(0.186,0.349, 0.581)	(0.209,0.419, 0.651)	(0.182,0.364, 0.591)	(0.186,0.326, 0.558)	(0.114,0.250, 0.477)
Supplier C	(0.442,0.674, 0.884)	(0.395,0.628, 0.837)	(0.250,0.477, 0.705)	(0.488,0.721, 0.953)	(0.227,0.455, 0.682)

Supplier D	(0.558,0.791,1.000)	(0.721,0.953,1.000)	(0.727,0.955,1.000)	(0.651,0.884,1.000)	(0.614,0.841,1.000)
Supplier E	(0.302,0.535,0.767)	(0.209,0.442,0.674)	(0.273,0.500,0.727)	(0.372,0.605,0.837)	(0.273,0.477,0.705)
Supplier F	(0.186,0.419,0.651)	(0.209,0.395,0.628)	(0.136,0.341,0.568)	(0.256,0.419,0.651)	(0.205,0.386,0.614)

Step 3: Develop the Weighted Normalized Decision Matrix

Weighted Normalized Decision Matrix: At this stage, the weighted normalized decision matrix is developed by incorporating weights assigned for each criterion. It is obtained by multiplying the values of the normalized decision matrix by the weight of each criterion. Thus, the weighted normalized decision matrix is a product of normalised values and weights of the criteria that gives scaled evaluation with regard to the relative importance of each criterion. The following table shows the resulting matrix when these weights are combined.

Table 6 The weighted normalized decision matrix

	EP	SR	EcP	TC	AS
Supplier A	) 0.107,0.153,0.1 (95	) 0.107,0.153,0.1 (91	) 0.077,0.118,0.1 (64	) 0.084,0.130,0.1 (77	) 0.077,0.123,0.1 (68
Supplier B	) 0.037,0.070,0.1 (16	) 0.042,0.084,0.1 (30	) 0.036,0.073,0.1 (18	) 0.037,0.065,0.1 (12	) 0.023,0.050,0.0 (95
Supplier C	) 0.088,0.135,0.1 (77	) 0.079,0.126,0.1 (67	) 0.050,0.095,0.1 (41	) 0.098,0.144,0.1 (91	) 0.045,0.091,0.1 (36
Supplier D	) 0.112,0.158,0.2 (00	) 0.144,0.191,0.2 (00	) 0.145,0.191,0.2 (00	) 0.130,0.177,0.2 (00	) 0.123,0.168,0.2 (00
Supplier E	) 0.060,0.107,0.1 (53	) 0.042,0.088,0.1 (35	) 0.055,0.100,0.1 (45	) 0.074,0.121,0.1 (67	) 0.055,0.095,0.1 (41
Supplier F	) 0.037,0.084,0.1 (30	) 0.042,0.079,0.1 (26	) 0.027,0.068,0.1 (14	) 0.051,0.084,0.1 (30	) 0.041,0.077,0.1 (23

Step 4: Identify the Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS)

First, in this step, FPIS and FNIS are calculated for the alternatives. Values of FPIS are calculated by choosing maximum value of the alternatives w.r.t. the criteria which consider higher score as beneficial. On the other hand, minimum value of the alternative is chosen for those criteria which consider lower score as beneficial. The converse is that FNIS is obtained through the minimum values in the case of criteria benefiting from high scores and maximum values in those benefiting from low scores. Thus, the FPIS and FNIS are the best and worst possible solutions for each criterion at hand, respectively. These ideal solutions are summarized in the table below.

Table 7 The positive and negative ideal solutions

	Positive ideal	Negative ideal
EP	(0.112,0.158,0.200)	(0.037,0.070,0.116)
SR	(0.144,0.191,0.200)	(0.042,0.079,0.126)
EcP	(0.145,0.191,0.200)	(0.027,0.068,0.114)
TC	(0.130,0.177,0.200)	(0.037,0.065,0.112)
AS	(0.123,0.168,0.200)	(0.023,0.050,0.095)

Step 5: Calculate the Distance from the Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS)

Steps for this section are to calculate the distance of each alternative from FPIS and FNIS. Thereafter, each alternative will have some distance from FPIS and FNIS in terms of some distance metric of fuzzy numbers. In particular, the distance to FPIS is computed by the sum of the distances between each alternative and FPIS for all criteria, and distance to FNIS is computed by the sum of distances between each alternative and FNIS for all criteria. The distance between two triangular fuzzy numbers is measured by taking the square root of the average of squared differences between their parameters. This then produces sharp numerical values for the respective distances from both the positive and negative ideal solutions. Calculated distances are shown in the table below.

Table 8 Distance from positive and negative ideal solutions

	Distance from positive ideal	Distance from negative ideal
Supplier A	0.178	0.323
Supplier B	0.487	0.01
Supplier C	0.265	0.236
Supplier D	0	0.496
Supplier E	0.338	0.163
Supplier F	0.445	0.053

Step 6: Calculate the Closeness Coefficient and Rank the Alternatives

The closeness coefficient of each alternative has been calculated in this step, which depicts just how closely each alternative will approach the FPIS with a distance from the FNIS. The formula for the closeness coefficient calculates the distance of the FNIS divided by the summation of distances from both FPIS and FNIS. It depicts which of the given alternatives is closer to the ideal solution and hence more preferable. The alternative having the maximum closeness coefficient will be treated as more favorable because of the best compromise in being as close to FPIS and as far from FNIS. The below table summarizes calculated closeness coefficients with a ranking of the alternatives:.

Table 9 Closeness coefficient

	Ci	rank
Supplier A	**0.644**	**2**
Supplier B	**0.021**	**6**
Supplier C	**0.472**	**3**
Supplier D	**1**	**1**
Supplier E	**0.325**	**4**
Supplier F	**0.107**	**5**

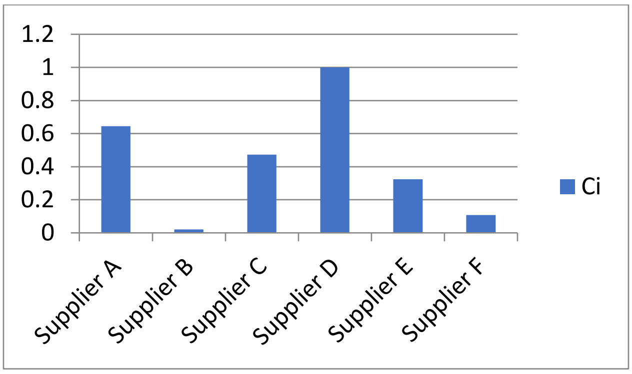

Figure 2 Closeness coefficient of different alternatives

The outcome of the current research study, as illustrated by the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution-Fuzzy TOPSIS, positions Supplier D as the best, with a score of 1, indicating that its performance has been very well and efficient for all the analyzed criteria. Supplier A has a close second rating of 0.644, meaning that in many aspects, it remains highly competitive in sustainability. Supplier C ranks third with 0.472, underlining that the companies are really contributing to the economic and environmental criteria. The fourth, fifth, and sixth positions are occupied by Suppliers E, F, and B, respectively, reflecting partial compliance with sustainability goals. These findings confirm that the Fuzzy TOPSIS technique is valid in the quantitative ranking and assessment of the performance of suppliers about their greening practice, social responsibility, economic performance, technological capability, and after-sales service, so as to support decision-makers to identify and select those raw material suppliers whose practices best fit the objectives of sustainability in the green supply chain management frameworks.

5. Discussion

The present research has established that the application of the Fuzzy TOPSIS method in the selection of sustainable suppliers in green supply chain management can draw valuable inferences while ranking suppliers according to multi-criteria. This study effectively merges the integration of fuzzy logic together with the TOPSIS method in order to handle the inherent uncertainties and vagueness that are related to the sustainability metrics, which often have been shunned by traditional methods. Results emphasize that the best compromise was Supplier D, which had the minimum distance from the positive ideal solution and maximum distance from the negative ideal solution. This is an indication of how the Fuzzy TOPSIS method can greatly improve decision-making in a green supply chain using a structured framework for the evaluation of suppliers.

This research is important because it can develop an integral approach to supplier selection that considers environmental, social, economic, technological, and after-sales criteria. It also allows an organization to make better decisions with the multidimensional assessment model that would lead to or enhance sustainability performance. Applying fuzzy logic to the research takes into consideration non-clearness and subjectivity in sustainability assessment, offering a more subtle, flexible tool for a decision-maker. These findings bring to light that for one to create sustainability and environmental responsibility effectively, there needs to be advanced techniques of decision-making.

The findings of the research have important applications for businesses looking to improve their green supply chain procedures. Organisations can systematically assess suppliers using economic, social, and environmental factors by implementing the suggested Fuzzy TOPSIS framework, guaranteeing alignment with sustainability goals. Decision-makers can make better decisions that support long-term sustainability, operational effectiveness as well as environmental responsibility by using this structured method to assist them overcome supplier selection uncertainty. This research also contributes significantly to the general area of green supply chain management through an innovative application of fuzzy TOPSIS that can be applied easily in other industrial contexts. The approach is deserving to add to the already available pool of knowledge, given the practical implications that an organization may steer toward its advantages in sustainability performances. This research opens the way for future studies and practical applications in green supply chain management due to the fact that, in this paper, all those gaps were covered in the traditional supplier selection methods with an utmost detailed evaluation framework.

6. Conclusion

The present study has applied the Fuzzy TOPSIS technique in selecting and ranking suppliers in green supply chain management. The output identifies Supplier D as the best performer that gains full marks to show ideal performance in all studied criteria. Supplier A follows closely after, portraying its good environmental practices and technological capabilities. The study has thus concentrated on including overall sustainability criteria involving environmental, social, economic, technological, and after-sales service for the selection of suppliers. The organizations can take assistance from the advanced decision-making techniques such as the Fuzzy TOPSIS in order to enhance the capacity of selection of suppliers that meets the operational needs and sustainability goals, thus enabling ecological responsibility and long-term sustainability of supply chain operations. Going forward, further research and application of such methods will continue to be needed in order to adapt to emerging sustainability challenges and advance the adoption of responsible practices globally for supply chains. To enhance criteria weighting and interdependencies, one possible approach is to use extra multi-criteria decision-making (MCDM) tools, such as fuzzy decision-making trial and evaluation laboratory (F-DEMATEL) or fuzzy analytic hierarchy process (F-AHP). Using machine learning and artificial intelligence (AI) tools to automate and optimise the supplier selection process is another potential approach that can improve decision accuracy and lessen human bias.

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