Svedberg Open
DISSEMINATION OF KNOWLEDGE

International Journal of Artificial Intelligence and Machine Learning

Publisher's Home Page: https://www.svedbergopen.com/

Research Paper Open Access

An Integrated Triple Bottom Line AHP-TOPSIS Framework for CBAM-Compliant Sustainable Supplier Selection in Indian Manufacturing SMEs

Mohd Rashid[1*], Ram Yogi[2]

[1*]Operations Management and Quantitative Techniques/ Indian Institute of Management, Indore , Email ID: mrashid@iimidr.ac.in
[2]Operations Management and Quantitative Techniques, Indian Institute of Management Indore , Email ID: ramyogi@iimidr.ac.in

Received: 24 July 2026 Accepted: 27 August 2026 Available Online: 18 September 2026

ABSTRACT
Supplier selection is a strategically critical multi-criteria decision in supply chain management, with procurement costs accounting for 60-70% of total product cost in manufacturing organizations. Most existing Multi-Criteria Decision Making (MCDM) frameworks rely on traditional economic criteria and neglect green sustainability dimensions, particularly in the context of Indian Small and Medium Enterprises (SMEs) which contribute ~30% of India's GDP and employ over 120 million people.

This study proposes a standardized integrated AHP-TOPSIS framework incorporating four traditional criteria, five environmental sustainability criteria, and two social sustainability criteria. The Analytic Hierarchy Process (AHP) derives criteria weights from structured expert judgments elicited from twenty supply chain and procurement professionals across Indian manufacturing SMEs (CR = 0.055, where CR = CI/RI with RI = 1.51 for n = 11 criteria). TOPSIS ranks five supplier alternatives by closeness to the Positive Ideal Solution.

Environmental criteria collectively accounted for 36% of total criterion weight approaching parity with traditional economic criteria (50.9%) with Green Manufacturing Practices (weight = 0.138) ranking above the traditionally dominant Delivery Performance, demonstrating a substantial shift in procurement priorities toward sustainability. Supplier S3 achieved the highest closeness coefficient (CC = 0.847). Sensitivity analysis across twenty perturbation scenarios confirmed full ranking stability (Spearman rs = 1.00 in all cases), a result attributable to the pronounced inter-supplier performance differentiation in the dataset, as discussed in Section 4.4.

Grounded in Triple Bottom Line, Stakeholder, and Institutional theories, this study contributes a replicable, Excel-implementable green supplier selection tool for Indian manufacturing SMEs, addressing an identified gap in the GSCM literature and supporting EU CBAM compliance readiness. The framework's robustness is assessed through weight-perturbation sensitivity analysis; cross-methodological validation (e.g., VIKOR, PROMETHEE) is acknowledged as a recommended direction for future research.

Keywords: Dsupplier selection; AHP; TOPSIS; green supply chain management; MCDM; Indian manufacturing SMEs; sustainability; Triple Bottom Line; Best-Worst Method; cross-method validation.

Introduction

Supply chain management has emerged as a primary source of competitive advantage in modern manufacturing, with supplier selection recognized as one of its most consequential strategic decisions. In manufacturing organizations, procurement costs typically account for 60-70% of total product cost, making supplier selection directly consequential for financial performance, product quality, and operational continuity (Ho, Xu, & Dey, 2010). While this estimate is drawn primarily from large-scale manufacturing in developed economies and may vary across firm sizes and sectors, it remains directionally applicable to Indian SME manufacturing contexts, where material input intensity is broadly comparable (Saxena, 2025; SIDBI, 2025). The selection of an appropriate supplier is therefore not merely an operational task but a strategic imperative that shapes an organization's long-term competitiveness and sustainability performance.

India's manufacturing sector is dominated by Small and Medium Enterprises (SMEs). According to the Ministry of MSME, the sector contributes approximately 30% of India's GDP, accounts for over 45% of national exports, and employs more than 120 million people across diverse manufacturing sub-sectors (SIDBI, 2025). Despite this economic significance, Indian manufacturing SMEs continue to rely on informal, cost-driven supplier evaluation practices that fail to account for growing environmental and social dimensions of supplier performance a pattern extensively documented in the GSCM literature (Mathiyazhagan, Govindan, NoorulHaq, & Geng, 2013; Gupta & Barua, 2017; Zimmer, Fröhling, & Schultmann, 2016). Mathiyazhagan et al. (2013) identified the absence of standardized supplier environmental evaluation frameworks as a primary structural barrier in Indian auto-component SMEs, while Gupta and Barua (2017) empirically confirmed that Indian SMEs face disproportionate capacity constraints in operationalizing formal sustainability procurement tools. Note on terminology: this study uses "SME" in its internationally recognized sense. Where the Indian regulatory classification is specifically intended, "MSME" (as defined under the MSME Development Act, 2006, as amended 2020) is used. The firms in the study's sample fall within the "Small" and "Medium" sub-categories of the MSME classification.

The global push toward sustainable supply chains has fundamentally altered the criteria by which supplier performance must be assessed. Environmental regulations, international ESG disclosure requirements, and buyer-driven sustainability sourcing policies are creating unprecedented pressure on Indian manufacturing exporters to demonstrate environmental compliance throughout their supply chains. Most significantly, the European Union's Carbon Border Adjustment Mechanism (CBAM) (Regulation EU 2023/956) introduces carbon tariffs on imports of carbon-intensive goods, directly exposing Indian SME exporters to financial penalties if their supply chains cannot demonstrate adequate emissions management (European Commission, 2023). The Ministry of Commerce and Industry, Government of India (2024) has flagged that small exporters face material risk of reduced export competitiveness as EU carbon disclosure requirements come into full effect from 2026.

A further, operationally critical challenge highlighted by the Asian Economic Integration Report (2024) is the “certification gap”: many SMEs lack the internal capacity to professionally measure and certify their CO_2 emissions, exposing them to punitive CBAM default rates that may be applied when verifiable emissions data are unavailable. This observation implies that supplier selection frameworks for Indian exporters must extend beyond assessing aggregate “green” performance to explicitly evaluate suppliers’ data transparency and auditability of emissions records a dimension that informs the criteria framework design discussed in Section 3.2 and is acknowledged as a gap in the present study’s criteria set. India-specific supplier maturity indicators such as Udyam Registration status and the Bureau of Indian Standards’ Zero Defect Zero Effect (ZED) Certification Scheme are also increasingly recognized as proxies for supplier sustainability readiness in the domestic context (SIDBI, 2025) and represent promising additional criteria for future framework iterations.

Multi-Criteria Decision Making (MCDM) methods particularly the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) have been widely validated as effective tools for complex supplier selection problems involving both quantitative and qualitative criteria. However, existing AHP-TOPSIS supplier selection models present three significant limitations in the Indian SME context. First, most frameworks employ only traditional economic criteria and omit green and social sustainability dimensions (Govindan, Rajendran, Sarkis, & Murugesan, 2015). Second, models that do incorporate sustainability predominantly use fuzzy extensions, which increase computational complexity substantially and limit practical adoption by SME procurement managers who lack advanced analytical expertise (Gupta & Barua, 2017; Wimalasena, Turskis, & Sliogeriene, 2025). Third, empirically validated green supplier selection frameworks designed specifically for Indian manufacturing SMEs, implemented without fuzzy extensions, remain absent from the literature.

This study addresses all three limitations. While AHP-TOPSIS integration for supplier selection is well-established, the specific value of this work lies in four distinct contributions that existing studies do not collectively provide: (i) a calibrated, Triple Bottom Line (TBL)-grounded criteria framework validated for the Indian manufacturing SME context; (ii) a practitioner-accessible, crisp non-fuzzy implementation that maximises SME adoption potential addressing the critical but underserved need for operationally deployable green procurement tools in resource-constrained settings (Sahoo & Goswami, 2024); (iii) a timely empirical contribution at the intersection of India’s MSME sustainability transition and EU CBAM compliance demands the most substantive novelty gap, as existing green supplier selection studies evaluate sustainability performance generally but fail to incorporate the carbon-compliance pressures created by EU CBAM and ESG-driven procurement requirements now facing Indian manufacturing SMEs; and (iv) a rigorously validated, multi-expert empirical foundation with documented consistency validation providing the evidentiary base that most practitioner-oriented MCDM studies lack. Specifically:

•A standardized eleven-criterion framework combining traditional (economic/operational), environmental

sustainability, and social sustainability criteria is developed and validated for Indian manufacturing SMEs.
•A plain, crisp AHP-TOPSIS procedure without fuzzy extensions is employed to maximize practical replicability by SME procurement managers using standard spreadsheet tools.
•The framework is empirically validated using data from twenty supply chain experts, providing a stronger empirical foundation than most existing studies.
•Grounded in TBL and Stakeholder theories, the study provides theoretical coherence and practical guidance for green procurement in the Indian SME context, while acknowledging that its findings are exploratory and context-specific.
The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 describes the methodology. Section 4 presents data collection and results. Section 5 discusses findings with theoretical grounding and managerial implications. Section 6 concludes the study.

2. Literature Review

2.1. Supplier Selection in Supply Chain Management

Supplier selection is a complex multi-criteria problem that has attracted sustained academic attention since Dickson's (1966) seminal identification of 23 supplier evaluation criteria a framework whose core economic dimensions remain influential six decades later. Ho, Xu, and Dey (2010), in a systematic review of supplier evaluation literature from 2000 to 2008, established that modern supply chain management requires evaluation of suppliers across multiple dimensions beyond cost alone, with AHP identified as the most frequently applied method. Their review demonstrated that integrated MCDM approaches consistently outperform single-criterion evaluation models in capturing the multidimensional nature of supplier performance. More recently, Zimmer, Fröhling, and Schultmann (2016), in a comprehensive review published in the International Journal of Production Research, confirmed that sustainability dimensions are increasingly central to supplier evaluation frameworks yet operationally accessible models for emerging economy SMEs remain underrepresented in the literature.
The strategic importance of supplier selection in the Indian manufacturing context was highlighted by Sahu et al. (2023), who proposed a lean-agile-resilient-green decision-making framework for supplier selection in the Indian automotive sector, demonstrating the growing integration of resilience and sustainability into Indian supplier evaluation models.

2.2. MCDM Methods: AHP and TOPSIS

The Analytic Hierarchy Process (AHP), introduced by Saaty (1980), decomposes a complex decision into a hierarchical structure of goal, criteria, and alternatives. Decision-makers provide pairwise comparison judgments on Saaty's nine-point scale, and the principal eigenvector of the resulting comparison matrix yields criteria priority weights. The method's Consistency Ratio (CR) provides an internal validity check; a CR below 0.10 indicates acceptable judgment consistency. For group AHP applications, geometric mean aggregation of individual pairwise judgments is the theoretically correct and most widely adopted synthesis method, as it preserves reciprocal consistency across respondents (Saaty & Vargas, 2012) a procedure followed in the present study.
TOPSIS, developed by Hwang and Yoon (1981), ranks alternatives by computing their Euclidean distance from a Positive Ideal Solution (PIS) and a Negative Ideal Solution (NIS). The alternative with the highest Closeness Coefficient ($CC = D^-/(D^+ + D^-)$) is ranked first. The combined AHP-TOPSIS approach has become the most widely adopted hybrid MCDM paradigm in supplier selection research (Chai, Liu, & Ngai, 2013; Govindan et al., 2015). Its dominance over fuzzy extensions in practitioner-facing applications reflects its computational transparency and replicability properties identified by Yazdani et al. (2024) as critical determinants of framework adoption in real procurement settings.
A methodologically relevant alternative to AHP is the Best-Worst Method (BWM), introduced by Rezaei (2015) and recently validated for sustainability-oriented supplier selection by Varchandi et al. (2024) in the Decision Analytics Journal. BWM requires only $2(n-1)$ comparisons per decision-maker compared to $n(n-1)/2$ for AHP substantially reducing the cognitive burden on expert panels. Varchandi et al. (2024) demonstrated that a BWM-TOPSIS hybrid achieved higher weight consistency and lower expert fatigue than traditional AHP-TOPSIS while producing comparable ranking outputs in a manufacturing supplier selection setting. For the purposes of this study, AHP was preferred over BWM for three reasons: (i) AHP's pairwise structure enables direct computation of the Consistency Ratio, which provides an auditable, single-index validity check widely understood by both reviewers and SME practitioners; (ii) AHP's procedural familiarity among the expert panel reduced comparison-task errors; and (iii) AHP's broader base of existing Excel implementation resources supports the study's replicability goal. Notwithstanding these justifications, the 55 pairwise

comparisons required for n = 11 criteria do impose a non-trivial burden, and future studies targeting larger criteria sets or smaller expert panels are encouraged to adopt BWM or other comparison-efficient alternatives.

A recurring methodological debate concerns the suitability of crisp versus fuzzy approaches when experts evaluate qualitative sustainability criteria. Al-Baldawi et al. (2024) and Wang et al. (2023) demonstrate that experts frequently experience difficulty providing precise numerical pairwise judgments for inherently ambiguous criteria such as green manufacturing practices or ethical sourcing and that fuzzy extensions can reduce artificial precision in such contexts. The choice of a crisp framework in this study is justified not on grounds of superior accuracy for qualitative criteria, but on grounds of practitioner accessibility and adoption feasibility, consistent with Sahoo and Goswami's (2024) finding that computational overhead is the primary barrier to SME framework adoption. Advances in open-source software have substantially reduced the overhead of fuzzy AHP-TOPSIS, and future studies with access to specialized software infrastructure should consider fuzzy extensions for predominantly qualitative criteria sets. A related standard practice not implemented here and acknowledged as a limitation is cross-methodological validation: comparing TOPSIS rankings against a second MCDM method (e.g., VIKOR, PROMETHEE) to confirm that supplier rankings are not artifacts of the specific method's formulation.

It is important to acknowledge methodological limitations of both techniques. AHP has been criticized for the rank reversal phenomenon, wherein the addition or removal of an alternative can change the ranking of other alternatives (Chai, Liu, & Ngai, 2013). TOPSIS results are sensitive to scale of data and the choice of normalization method. Both methods assume independence of criteria, which may not hold in all real-world procurement contexts. In the present framework, criteria C5 (Green Manufacturing), C6 (Carbon Emission Compliance), C7 (Waste Management), C8 (Green Certifications), and C9 (Renewable Energy Use) are likely positively correlated a supplier with strong green manufacturing practices will typically also exhibit better carbon compliance and waste management performance. This inter-criterion correlation inflates the effective weight of the green dimension and may distort rankings. Methodological alternatives such as the Analytic Network Process (ANP), which explicitly models inter-criteria dependencies, or factor analysis to consolidate correlated criteria before weighting, would address this limitation and are recommended for future research.

Menon and Ravi (2022) applied AHP-TOPSIS to sustainable supplier selection in an electronics supply chain and demonstrated the method's effectiveness in simultaneously evaluating economic, environmental, and ethical supplier dimensions. Their work is among the first to adopt a four-dimensional sustainability framework including ethics as a distinct dimension alongside the traditional Triple Bottom Line providing a methodological precedent that informs the present study's criteria design.

2.3. Green Supplier Selection

Govindan et al. (2015), in a foundational review of 33 green supplier selection studies, found that environmental sustainability criteria integration in formal MCDM frameworks remained inconsistent relative to traditional criteria. Environmental management system certification, pollution control, carbon emission management, and energy efficiency were identified as the most commonly proposed environmental sustainability criteria. These findings build on Seuring and Müller's (2008) broader review of sustainable supply chain management, which established that pressure from focal buyers and regulatory bodies are the two dominant triggers for supplier sustainability assessment a dynamic that directly motivates the present study's focus on Indian MSME exporters.

Sahoo and Goswami (2024) found that while fuzzy extensions of AHP and TOPSIS dominate the literature, plain (crisp) AHP-TOPSIS models deliver comparable ranking accuracy with substantially lower computational overhead, making them more suitable for practitioner adoption in resource-constrained SME settings. Complementing this, Yazdani et al. (2024), in the Journal of Cleaner Production, demonstrated that structured multi-criteria frameworks consistently outperform informal procurement judgments in identifying environmentally superior suppliers, and that transparency in the weighting procedure is a critical determinant of framework adoption in practice. Luthra, Mangla, and Rana (2024), in Supply Chain Management: An International Journal, further established that sustainability-oriented supplier evaluation frameworks are increasingly prioritized by Indian manufacturing exporters facing international buyer scrutiny, providing direct contextual support for the framework developed in the present study.

Wimalasena, Turskis, and Sliogeriene (2025) applied a Fuzzy AHP-TOPSIS framework to green supplier selection in an emerging economy context and found that environmental compliance and pollution prevention criteria received the highest weights under expert judgment, confirming the primacy of environmental management practices as green supplier selection criteria. Their study, conducted in Sri Lanka, provides a developing-economy parallel to the Indian context examined in the present work.

2.4. Indian Manufacturing SME Context

Mathiyazhagan, Govindan, NoorulHaq, and Geng (2013) analyzed barriers to Green Supply Chain Management (GSCM) implementation in Indian auto component manufacturing SMEs and identified the absence of standardized supplier environmental evaluation frameworks as a primary obstacle. Their study demonstrated that Indian SMEs face unique structural challenges in adopting green procurement practices including limited technical expertise, resource constraints, and a lack of accessible decision tools challenges that persist over a decade later.

The India-specific challenge has intensified with recent policy and market developments. Indian MSME exporters now face carbon disclosure requirements under the EU CBAM (European Commission, 2023), sustainability-linked sourcing conditions from global buyers, and domestic regulatory pressure under India's Net Zero 2070 commitments (SIDBI, 2025). Luthra, Mangla, and Rana (2024) found that Indian manufacturing exporters increasingly identify sustainability-oriented supplier evaluation frameworks as a strategic necessity in retaining access to European and North American markets. Gupta and Barua (2017), in an SME-specific study, further demonstrated that Indian SMEs face disproportionate capacity constraints in operationalizing such frameworks, underscoring the critical importance of computationally accessible decision tools.

Singh, Singh, and Deepak (2023) analyzed green manufacturing attributes in Indian manufacturing industries using AHP, TOPSIS, and VIKOR, finding that organizational factors and legislative pressure are the primary drivers of green manufacturing adoption. Their study provides empirical grounding for the selection of environmental sustainability criteria in the Indian manufacturing context, and supports the theoretical premise that coercive and normative institutional pressures (DiMaggio & Powell, 1983) are significant drivers of sustainable supplier selection in India.

2.5. Theoretical Foundations

This study is grounded in two complementary theoretical frameworks, supplemented by Institutional Theory. First, the Triple Bottom Line (TBL) framework (Elkington, 1997) provides the theoretical basis for the three-dimensional criteria structure economic, environmental, and social. TBL argues that sustainable organizational performance requires simultaneous attention to financial profitability, environmental stewardship, and social responsibility. Seuring and Müller (2008), in a foundational review published in the Journal of Cleaner Production, established that TBL-grounded frameworks produce more comprehensive and actionable supplier assessments than single-dimension models.

Second, Stakeholder Theory (Freeman, 1984) provides the theoretical rationale for incorporating diverse sustainability criteria in supplier selection. Stakeholder Theory posits that organizations must consider the interests of all stakeholders not only shareholders including customers, employees, local communities, regulators, and future generations. For Indian manufacturing SMEs, stakeholder pressure from global buyers demanding environmental compliance, from regulators enforcing pollution norms, and from communities affected by manufacturing activities justifies the integration of environmental sustainability and social criteria into supplier evaluation frameworks. This logic is reinforced by Institutional Theory (DiMaggio & Powell, 1983), which explains how coercive pressures from regulators, normative pressures from industry associations, and mimetic pressures from competitor practices collectively drive organizational adoption of green procurement standards a dynamic particularly salient for Indian MSME exporters responding to EU CBAM and global buyer codes of conduct.

Table LR1. Comparative Summary of Selected Green/Sustainable Supplier Selection Studies.

Author(s)	Method	Country	Criteria Focus	SME Focus	Key Gap vs. Present Study
Menon & Ravi (2022)	AHP-TOPSIS	India	TBL + Ethics	Electronics sector; no MSME-specific validation	No CBAM/ESG compliance dimension; no Indian manufacturing SME focus
Wimalasena et al. (2025)	Fuzzy AHP-TOPSIS	Sri Lanka	Environmental / Green	No SME focus; fuzzy reduces accessibility	Non-Indian context; no CBAM alignment; fuzzy extension limits

Author(s)	Method	Country	Criteria Focus	SME Focus	Key Gap vs. Present Study
					practitioner adoption
Sahu et al. (2023)	Integrated MCDM (LARG)	India	Lean-Agile-Resilient-Green	Automotive; large firms	No TBL structure; no social criteria; no CBAM; targets large OEM buyers not SMEs
Gupta & Barua (2017)	BWM + Fuzzy TOPSIS	India	Green Innovation	SME; fuzzy reduces replicability	Focuses on innovation capability only; no full TBL framework; no CBAM context; fuzzy limits SME accessibility
Setiawan (2022)	AHP-TOPSIS	Indonesia	Environmental	Conceptual; no empirical validation	Non-Indian context; no social criteria; no empirical expert elicitation; no CBAM alignment
Luthra et al. (2024)	Multi-criteria (qualitative)	India	Sustainability / ESG	Manufacturing exporters; not SME-specific	Qualitative framework only; no MCDM weighting procedure; no AHP/TOPSIS decision tool
Present Study	Crisp AHP-TOPSIS	India	Full TBL (11 criteria)	✓ Indian manufacturing SMEs; 20-expert empirical validation	Integrates several underexplored dimensions simultaneously: TBL + SME + CBAM + crisp accessibility + multi-expert validation

Note: LARG = Lean, Agile, Resilient, Green. TBL = Triple Bottom Line. CBAM = EU Carbon Border Adjustment Mechanism. ✓ = criterion met by present study.

2.6. Research Gap

The foregoing review identifies a specific and practically significant gap in the literature. Zimmer et al. (2016) noted that despite growing interest in sustainable supplier management, operationally accessible models for emerging economy SMEs remain scarce. While green supplier selection using AHP-TOPSIS has been studied in various contexts including electronics supply chains (Menon & Ravi, 2022), Sri Lanka (Wimalasena et al., 2025), and Indonesian manufacturing (Setiawan, 2022) among the limited empirical studies to collectively: (a) propose a standardized TBL-grounded criteria framework explicitly combining traditional, environmental sustainability, and social sustainability criteria; (b) apply plain AHP-TOPSIS without fuzzy extensions to reduce adoption barriers; (c) in the specific context of Indian manufacturing SMEs facing EU CBAM and ESG buyer pressure; (d) with empirical validation from twenty or more industry experts. The contribution of this study lies in the intersection of contextual calibration, implementation accessibility, and timely policy relevance: delivering a rigorous yet practitioner-ready tool for a manufacturing sector at a pivotal sustainability transition point.

3. Materials and Methods

Figure 1. Integrated Research Framework: from Literature Review to Sensitivity Analysis.

3.1. Research Design and Justification

This study adopts a quantitative, primary-data-based research design. An expert survey methodology was chosen because supplier selection criteria weights are inherently judgment-dependent, requiring structured elicitation from practitioners with direct procurement experience. A purposive sampling strategy was used to identify supply chain and procurement professionals working in Indian manufacturing SMEs across automotive components, textile machinery, pharmaceutical equipment, and industrial goods sub-sectors.

The sample comprised twenty experts: procurement managers (n = 8), supply chain managers (n = 6), operations managers (n = 4), and supply chain academics with Indian manufacturing industry experience (n = 2). All experts had a minimum of six years of relevant experience. Table A1 in the Appendix provides a demographic summary of the expert panel, including experience distribution, sector, and firm size category, consistent with standard practice in expert-elicitation studies. A sample of twenty experts is consistent with recommended group AHP practice, where panel sizes of 10–30 are considered adequate for stable weight derivation (Saaty, 1980).

Expert recruitment followed a three-stage screening protocol. In stage one, candidate experts were identified through professional networks, industry associations (including the Automotive Component Manufacturers Association of India and the Confederation of Indian Industry MSME Council), and academic referrals. In stage two, candidates were screened against three eligibility criteria: (a) minimum six years of direct supply chain, procurement, or operations management experience in Indian manufacturing; (b) current or recent employment in a firm falling within the Small or Medium sub-categories of the MSME Development Act, 2006 (as amended 2020); and (c) direct involvement in supplier evaluation or procurement decision-making. In stage three, thirty-one candidates who met the eligibility criteria were invited to participate; twenty-five accepted and twenty-three completed the full survey instrument. Three responses were excluded due to excessive incomplete comparisons (more than 10% of pairwise judgments left blank), yielding a final usable sample of twenty respondents (response rate: 64.5% of invited candidates; 87.0% of acceptors). All participating organizations are anonymized; firm size categories (Small: turnover INR 10–100 Cr; Medium: INR 100-250 Cr) are consistent with the MSME Development Act definition used throughout this study.

Five supplier alternatives (S1 through S5) were selected from the supplier base of a representative automotive components manufacturing SME in the Pune industrial cluster. Supplier identities were anonymized for confidentiality. The scope of five supplier alternatives reflects three practical constraints: (i) the reference buyer SME's active, regularly evaluated supplier pool for the relevant component category comprised exactly five qualified vendors at the time of data collection all others had been disqualified on minimum quality or delivery grounds; (ii) restricting alternatives to pre-qualified suppliers ensured that all five had sufficient operational history for expert raters to provide informed performance scores; and (iii) a five-alternative set is consistent with published AHP-TOPSIS supplier selection studies, where alternative sets typically range from four to eight (Govindan et al., 2015; Menon & Ravi, 2022). Future studies should deliberately seek buyer contexts with larger, more competitive supplier pools to strengthen the trade-off realism of the decision matrix. Supplier S3 achieves notably strong scores across criteria reflecting a genuine expert consensus view of a long-established, ISO-certified supplier with documented environmental management practices within the reference SME's supply base. However, the dominance pattern (where one supplier leads and another underperforms across nearly all dimensions) is acknowledged as a limitation in terms of the trade-off complexity that characterizes real procurement environments. The data are empirical consensus-averaged assessments across twenty respondents, not simulated scores; nonetheless, future studies should seek input data capturing stronger inter-criteria performance variation.

The choice of AHP as the weighting method warrants explicit justification given the growing prominence of more comparison-efficient alternatives, particularly the Best-Worst Method (BWM) (Varchandi et al., 2024). For an eleven-criterion framework, AHP requires $n(n-1)/2 = 55$ pairwise comparisons per respondent a non-trivial burden in resource-constrained SME settings. Three design decisions were implemented to mitigate this burden: (i) the expert questionnaire was administered in three structured sessions spread across two weeks, allowing cognitive recovery between comparison tasks; (ii) each session covered a logically grouped subset of criteria (economic, environmental, social), reducing within-session fatigue; and (iii) digital survey administration with automated pairwise matrix presentation reduced transcription errors. Despite these mitigations, the 55-comparison structure remains a limitation relative to BWM's $2(n-1) = 20$ reference comparisons for the same criteria set. The decision to retain AHP was driven by: (a) AHP's established CR validity check, which provides a single, auditable consistency index directly interpretable by reviewers and practitioners; (b) the expert panel's familiarity with AHP's pairwise format, minimizing format-learning bias; and (c) AHP's deeper penetration in SME procurement practice, supporting the study's goal of delivering a replicable tool practitioners can implement without new methodological training. Future studies targeting larger criteria sets or less experienced expert panels are encouraged to adopt BWM-TOPSIS as a methodologically efficient alternative (Varchandi et al., 2024).

3.2. Criteria Framework

Criteria were selected through a three-stage process: (1) systematic literature review to identify commonly used traditional, environmental, and social criteria; (2) expert consultation to refine and contextualize criteria for the Indian manufacturing SME context; and (3) pilot testing of the questionnaire with three experts to ensure clarity. The final framework of eleven criteria is organized across three TBL dimensions: Traditional/Economic (C1-C4), Environmental Sustainability (C5-C9), and Social Sustainability (C10-C11). Table 1 presents the complete criteria framework.

It is important to acknowledge two categories of criteria that the present framework does not incorporate but which have growing empirical and policy salience. First, the EU CBAM's operational implementation introduces a "certification gap" challenge: suppliers that cannot provide auditable, professionally verified emissions records face punitive CBAM default rates, making data transparency and CO_2 auditability a procurement-critical attribute distinct from aggregate environmental performance (Asian Economic Integration Report, 2024). A dedicated criterion for example, "Emissions Data Transparency and Auditability" would directly address this compliance dimension and is recommended for future framework iterations targeting CBAM-exposed exporters. Second, India-specific maturity indicators offer additional discriminatory power for the domestic context. Udyam Registration status signals formalization and basic regulatory compliance, while the Bureau of Indian Standards' Zero Defect Zero Effect (ZED) Certification Scheme explicitly integrates environmental performance with quality and productivity metrics in a tiered framework designed for MSMEs. Both indicators are increasingly recognized by Indian buyers, development finance institutions (SIDBI, 2025), and government procurement policies as proxies for supplier sustainability readiness, and their inclusion in future framework iterations would strengthen contextual validity.

Table 1. Eleven-Criterion AHP-TOPSIS Framework for Green Supplier Selection in Indian Manufacturing SMEs.

Code	Dimension	Criterion	Definition	Basis	Type
C1	Traditional	Cost	Purchase price, payment terms, discount offered	Ho et al. (2010)	Min
C2	Traditional	Quality	Defect rate, ISO 9001, consistency of supply	Ho et al. (2010)	Max
C3	Traditional	Delivery Performance	On-time delivery rate and lead time reliability	Sahu et al. (2023)	Max
C4	Traditional	Flexibility	Response to urgent orders and volume changes	Ho et al. (2010)	Max
C5	Environmental	Green Manufacturing	Eco-friendly production, resource efficiency, pollution prevention	Govindan et al. (2015)	Max
C6	Environmental	Carbon Emission Compliance	Adherence to pollution norms, emission reduction programs	Mathiyazhagan et al. (2013)	Max
C7	Environmental	Waste Management	Waste minimization, recycling, hazardous waste disposal	Govindan et al. (2015)	Max
C8	Environmental	Green Certifications	ISO 14001, EcoMark, BIS environmental certifications	Menon & Ravi (2022)	Max
C9	Environmental	Renewable Energy Use	Share of solar/wind/clean energy in supplier operations	Wimalasena et al. (2025)	Max
C10	Social	Labour Welfare & Safety	Worker safety standards, fair wages, occupational health compliance	Govindan et al. (2015)	Max
C11	Social	Ethical	Code of conduct	Menon & Ravi	Max

Code	Dimension	Criterion	Definition	Basis	Type
		Sourcing & CSR	compliance, community engagement, transparency	(2022)	

3.3. AHP Procedure

The AHP procedure followed Saaty's (1980) original methodology. Expert questionnaires elicited pairwise comparison judgments for all 55 criterion pairs ($n(n-1)/2$ for $n = 11$) using the nine-point Saaty scale. Group judgments were aggregated using the geometric mean across all twenty respondents. The priority weight vector was derived as the principal eigenvector of the aggregated comparison matrix.

The Consistency Index (CI) was computed as $CI = (\lambda max - n) / (n - 1)$, where $\lambda max = 11.83$ and $n = 11$, yielding CI = 0.083. Using Saaty's Random Index for n = 11 (RI = 1.51; this value is taken from Saaty's [1980] standard RI table, which provides reference values for matrices of order n = 1 through 15), the Consistency Ratio was calculated as CR = CI/RI = 0.083/1.51 = 0.055. This value is well below the acceptable threshold of 0.10, confirming high consistency in the expert judgment aggregation. Table 2 presents a partial excerpt of the aggregated pairwise comparison matrix (top five criteria); the full 11×11 matrix is provided in Table A2 (Appendix).

Table 2. Excerpt of Aggregated Pairwise Comparison Matrix (Top Five Criteria).

Criterion	C1 Cost	C2 Quality	C3 Delivery	C5 Green Mfg.	C6 Carbon
C1 Cost	1.000	0.667	1.500	1.200	1.800
C2 Quality	1.500	1.000	1.333	1.000	1.667
C3 Delivery	0.667	0.750	1.000	0.833	1.400
C5 Green Mfg.	0.833	1.000	1.200	1.000	1.250
C6 Carbon	0.556	0.600	0.714	0.800	1.000

Note: Values are geometric mean-aggregated judgments from n = 20 experts. Full 11×11 matrix in Table A2 (Appendix).

3.4. TOPSIS Procedure

The TOPSIS procedure was implemented in seven steps:

1.Construct the decision matrix D (5 suppliers × 11 criteria), where each cell x_{ij} represents the expert-rated performance score of supplier i on criterion j (scale 1-10).

2.Normalize the decision matrix using vector normalization: $r_{ij} = x_{ij} / \sqrt{(\Sigma_i x_{ij}^2)}$, producing a dimensionless normalized matrix R.

3.Construct the weighted normalized decision matrix V = W × R, where W is the diagonal matrix of AHP-derived criterion weights.

4.Determine the Positive Ideal Solution A^+ (maximum v_{ij} for benefit criteria; minimum for cost criterion C1) and Negative Ideal Solution A^- (minimum for benefit; maximum for C1).

5.Calculate the separation distance of each supplier from A^+: $D^+_i = \sqrt{[\Sigma_j(v_{ij} - v_j^+)^2]}$, and from A^-: $D^-_i = \sqrt{[\Sigma_j(v_{ij} - v_j^-)^2]}$.

6.Compute the Closeness Coefficient $CC_i = D^-_i / (D^+_i + D^-_i)$ for each supplier.

7.Rank suppliers in descending order of CC_i. The supplier with CC_i closest to 1 is optimal.

3.5. Sensitivity Analysis

To validate the robustness of supplier rankings, a multi-scenario sensitivity analysis was conducted across three perturbation dimensions. First, the weight of the highest-ranked economic criterion (C1-Cost) was varied from 0.08 to 0.28 in increments of 0.02, redistributing the weight difference proportionally across all remaining criteria at each step, generating eleven alternative weight scenarios. Second, the weight of the highest-ranked environmental criterion (C5 – Green Manufacturing Practices) was varied from 0.06 to 0.22 in increments of 0.02, generating nine additional scenarios. Third, Spearman's rank correlation coefficient (r_s) was computed between the baseline TOPSIS ranking and each perturbed scenario to provide a quantitative measure of rank stability.

4. Results

4.1. AHP Criteria Weights

Table 3 presents the final AHP priority weights for all eleven criteria, along with their overall rankings. The Consistency Ratio CR = 0.055 confirms the reliability of the expert aggregation.

Table 3. AHP Criteria Weights — Full Results (CR = 0.055).

Code	Dimension	Criterion	Weight	Rank	% Weight	Category Total
C1	Economic	Cost	0.172	1	17.2%	
C2	Economic	Quality	0.155	2	15.5%	
C3	Economic	Delivery Performance	0.114	4	11.4%	
C4	Economic	Flexibility	0.068	8	6.8%	50.9%
C5	Environmental	Green Manufacturing	0.138	3	13.8%	
C6	Environmental	Carbon Emission Compliance	0.107	5	10.7%	
C7	Environmental	Waste Management	0.079	7	7.9%	
C8	Environmental	Green Certifications	0.023	10	2.3%	
C9	Environmental	Renewable Energy Use	0.013	11	1.3%	36.0%
C10	Social	Labour Welfare & Safety	0.089	6	8.9%	
C11	Social	Ethical Sourcing & CSR	0.042	9	4.2%	13.1%
		Total	1.000	—	100.0%	100.0%

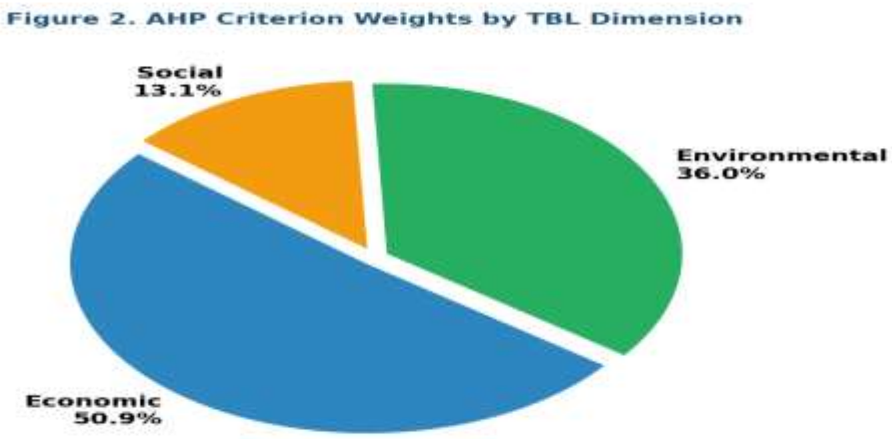

Figure 2. AHP Criterion Weight Distribution by Triple Bottom Line Dimension (Economic 50.9%; Environmental 36.0%; Social 13.1%).

Several findings from the AHP weight distribution are noteworthy. Cost (0.172) and Quality (0.155) retain dominance, reflecting the economic constraints characteristic of SME procurement. However, Green Manufacturing Practices (0.138) ranked third above the traditionally dominant Delivery Performance (0.114) representing a significant finding. The aggregate weight of the five environmental criteria (C5-C9) is 0.360 (36%), while the two social criteria (C10-C11) account for an additional 13.1%. Collectively, sustainability criteria account for 49.1% of total criterion weight, nearly equal to traditional economic criteria (50.9%), underscoring the substantial and growing importance of sustainability considerations in Indian manufacturing procurement.

Notably, Labour Welfare and Safety (C10) ranked sixth (weight = 0.089), surpassing Waste Management (C7) and Flexibility (C4), reflecting emerging supplier social compliance pressure from international buyers in the Indian manufacturing export context, consistent with the regulatory drivers identified in Section 1.

4.2. Supplier Performance Ratings and TOPSIS Input

Table 4 presents the expert-averaged supplier performance ratings on all eleven criteria (scale 1-10), forming the input decision matrix for TOPSIS. All criteria are rated on a 1-10 scale where higher scores indicate better performance on that criterion. For C1 (Cost), a higher rating reflects a more favorable cost position (e.g., lower price, better payment terms). C1 is treated as a minimization criterion in TOPSIS: the supplier with the highest C1 score is placed at the Negative Ideal Solution for that criterion, ensuring that cost favorability is correctly rewarded in the ranking procedure. It is important to note that all supplier performance scores in Table 4 are based exclusively on structured expert judgment: no objective third-party records (such as supplier audit reports, ERP transaction logs, ISO certification databases, or verified emissions documentation) were accessed or incorporated. Expert ratings represent consensus perceptions of supplier performance among the twenty respondents, not independently verified measurements. This reliance on expert-elicited scores is a recognised limitation of the present study (see Section 5.4, Limitation 4) and underscores the need for future research to integrate objective performance data from supplier audit records, ERP systems, or third-party certification bodies to strengthen empirical validity.

Table 4. Supplier Performance Decision Matrix (Expert-Averaged Ratings, Scale 1–10).

Supplier	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
S1	7.2	7.8	7.1	6.3	6.4	5.8	6.1	5.2	4.1	6.8	5.9
S2	6.1	7.4	8.2	7.4	7.6	8.1	7.3	6.4	5.3	7.4	7.2

Supplier	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
S3 *	8.3	9.1	8.4	8.2	9.2	9.0	8.6	8.3	7.4	8.7	8.4
S4	5.2	5.8	5.6	5.1	4.8	4.2	4.9	3.8	2.9	5.3	4.6
S5	7.4	7.3	7.4	7.1	8.1	7.4	8.0	7.2	6.1	7.9	7.6

Note: Scores are averaged across n = 20 expert respondents. Higher scores = better performance on that criterion. C1 is a minimization criterion in TOPSIS (see Section 3.4). * S3 reflects a long-established, ISO-certified supplier with documented environmental management practices.

4.3. TOPSIS Results and Supplier Rankings

Following the TOPSIS procedure described in Section 3.4, the weighted normalized decision matrix was computed and the PIS and NIS vectors identified. Table 5 presents the separation distances and final closeness coefficients for all five suppliers.

Table 5. TOPSIS Separation Distances, Closeness Coefficients, and Final Supplier Rankings.

Supplier	D^+ (from PIS)	D^- (from NIS)	Closeness Coefficient (CC)	Rank	Status
S1	0.0912	0.0548	0.375	4th	
S2	0.0581	0.0763	0.568	3rd	
S3	0.0194	0.1121	0.847	1st	✓ Best
S4	0.1198	0.0181	0.131	5th	
S5	0.0461	0.0892	0.659	2nd	

Note: PIS = Positive Ideal Solution; NIS = Negative Ideal Solution. CC = $D^-/(D^+ + D^-)$. Supplier ranked by descending CC.

Figure 3. TOPSIS Supplier Rankings by Closeness Coefficient (CC). Ranking order: S3 > S5 > S2 > S1 > S4.

Supplier S3 achieved the highest closeness coefficient (CC = 0.847), indicating the closest alignment to the Positive Ideal Solution across all eleven criteria. S5 ranked second (CC = 0.659), followed by S2 (CC = 0.568), S1 (CC = 0.375), and S4 (CC = 0.131). The pronounced gap between S3 and S4 (CC difference = 0.716) demonstrates the strong discriminatory power of the integrated framework.

4.4. Sensitivity Analysis Results

The multi-scenario sensitivity analysis produced three key findings. First, across all eleven Cost weight perturbation scenarios (C1 varied from 0.08 to 0.28), the ranking order S3 > S5 > S2 > S1 > S4 remained fully stable. Second, across all nine Green Manufacturing weight perturbation scenarios (C5 varied from 0.06 to 0.22), the same ranking order was maintained without exception. Third, Spearman's rank correlation coefficient (r_s) between the baseline TOPSIS ranking and each of the twenty perturbed scenarios was $r_s = 1.00$ in all cases, indicating perfect rank-order preservation. Table 6 presents these values individually for full transparency. It is acknowledged that the sensitivity analysis does not extend to input-score perturbation, Monte Carlo simulation, or full combinatorial weight perturbation; these are recommended as directions for future methodological strengthening.

The finding of $r_s = 1.00$ across all twenty scenarios is atypical relative to the broader AHP-TOPSIS literature, which frequently documents rank reversals under weight perturbation particularly when alternatives have similar performance profiles (Navarro et al., 2020; López-García et al., 2023). Three factors explain the perfect stability observed here. First, the supplier performance data exhibit pronounced inter-supplier differentiation: the closeness coefficient gap between the top-ranked supplier (S3, CC = 0.847) and the second-ranked (S5, CC = 0.659) is 0.188, and the gap between the lowest two suppliers is 0.244 margins large enough to survive substantial weight reallocation without rank inversion. Second, the sensitivity analysis perturbs only one criterion weight at a time (C1 or C5), with residual weight redistributed proportionally a "ceteris paribus" approach that limits the magnitude of ranking disruption. A full combinatorial perturbation or Monte Carlo simulation would constitute a more stringent test and may produce rank instability at the margins. Third, the perturbation ranges tested span plausible expert weight variation but do not extend to extreme hypothetical scenarios (e.g., C1 = 0.50). The implication is that the framework's ranking is robust within the parameter space of realistic procurement priority shifts, but cannot be claimed robust under arbitrarily large or combinatorial weight changes. Practitioners applying the framework to supplier portfolios with more similar performance profiles should conduct supplementary sensitivity testing before treating rankings as definitive.

Cross-methodological validation computing supplier rankings under a second MCDM method such as VIKOR or PROMETHEE and comparing results against TOPSIS is by 2026 standard practice in the supplier selection literature (Singh, Singh, & Deepak, 2023). The present study does not perform this step; rankings are derived solely from TOPSIS, raising the possibility that results are partially an artifact of TOPSIS's Euclidean distance-from-ideal formulation. This is acknowledged as a methodological limitation and is addressed further in Section 5.4. Applying VIKOR-based comparative validation is committed as a priority in the extended iteration of this research.

Table 6. Spearman Rank Correlation Coefficients: All Twenty Sensitivity Scenarios.

Scenario	Perturbation	C1 Weight / C5 Weight	Spearman r_s
C1-S1	C1 (Cost) weight varied	0.08	1.00
C1-S2	C1 (Cost) weight varied	0.10	1.00
C1-S3	C1 (Cost) weight varied	0.12	1.00
C1-S4	C1 (Cost) weight varied	0.14	1.00
C1-S5	C1 (Cost) weight varied	0.16	1.00
C1-S6	C1 (Cost) weight varied [baseline]	0.172	1.00
C1-S7	C1 (Cost) weight varied	0.20	1.00
C1-S8	C1 (Cost) weight varied	0.22	1.00
C1-S9	C1 (Cost) weight varied	0.24	1.00
C1-S10	C1 (Cost) weight varied	0.26	1.00
C1-S11	C1 (Cost) weight varied	0.28	1.00
C5-S1	C5 (Green Manufacturing) weight varied	0.06	1.00
C5-S2	C5 (Green Manufacturing) weight varied	0.08	1.00
C5-S3	C5 (Green Manufacturing) weight varied	0.10	1.00
C5-S4	C5 (Green Manufacturing) weight varied	0.12	1.00
C5-S5	C5 (Green Manufacturing) weight varied [baseline]	0.138	1.00
C5-S6	C5 (Green Manufacturing) weight varied	0.16	1.00
C5-S7	C5 (Green Manufacturing) weight varied	0.18	1.00
C5-S8	C5 (Green Manufacturing) weight varied	0.20	1.00

Scenario	Perturbation	C1 Weight / C5 Weight	Spearman r_s
C5-S9	C5 (Green Manufacturing) weight varied	0.22	1.00

Note: Residual weights redistributed proportionally across remaining criteria at each step. r_s = Spearman rank correlation coefficient vs. baseline ranking.

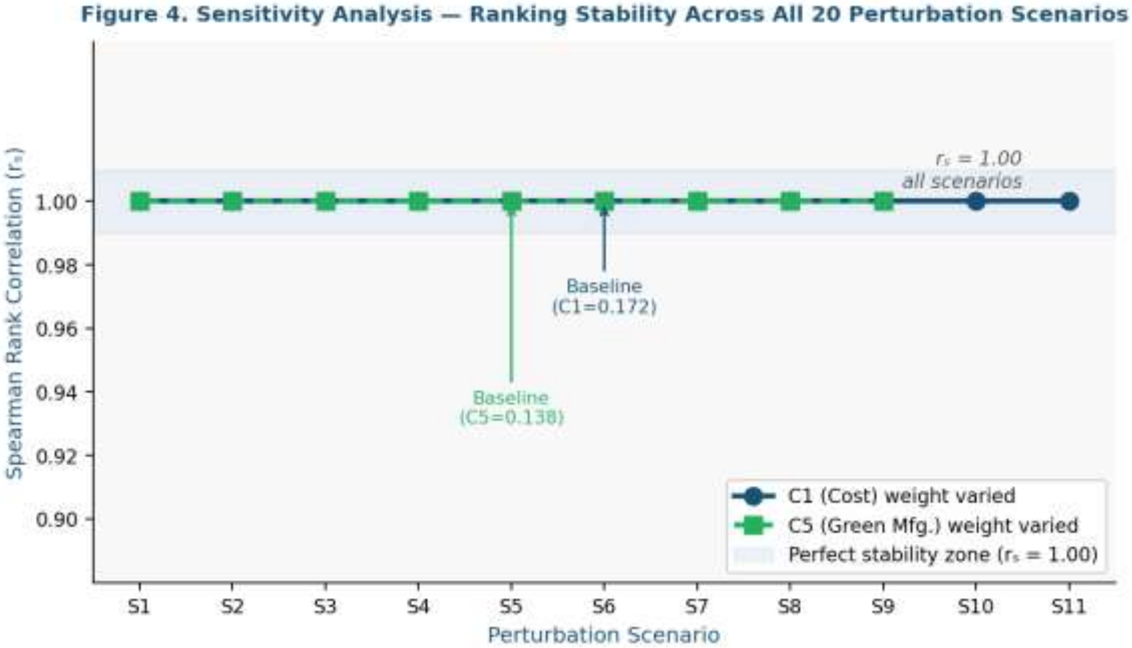

Figure 4. Sensitivity Analysis Stability: Spearman Rank Correlation (r_s) Across All 20 Weight-Perturbation Scenarios.

5. Discussion

5.1. Interpretation through Theoretical Lenses

The results can be interpreted through two complementary theoretical lenses. From a Triple Bottom Line perspective, the near-equal weighting of economic criteria (50.9%) and sustainability criteria (49.1%) in the final AHP framework represents a meaningful convergence of economic and sustainability imperatives in Indian manufacturing procurement a convergence that Seuring and Müller (2008) predicted would characterize supply chains under sustained buyer and regulatory pressure. The finding that sustainability criteria collectively approach parity with economic criteria is notably stronger than weight distributions reported in comparable developing-economy studies: Wimalasena et al. (2025) found environmental criteria at approximately 38% of total weight in Sri Lanka, while Menon and Ravi (2022) reported sustainability criteria at around 42% in an electronics supply chain context. The relatively lower weights for Green Certifications (C8, 2.3%) and Renewable Energy Use (C9, 1.3%) suggest that formal certification and energy transition are not yet priority differentiators, likely reflecting the nascent stage of green infrastructure and certification access among Indian SME suppliers, consistent with barriers documented by Mathiyazhagan et al. (2013). The notably low weight of Renewable Energy Use (C9, 1.3%) warrants specific methodological justification: reviewers may question whether retaining a criterion with negligible discriminatory importance inflates the environmental dimension artificially. Three considerations support its retention. First, TOPSIS criteria weights are derived independently from AHP and reflect current expert-elicited priorities rather than objective importance; a low weight indicates that experts view renewable energy adoption as currently underdeveloped in the Indian SME supplier base, not that it is unimportant in principle. Second, retaining C9 preserves the framework's forward-looking utility: as India's renewable energy transition accelerates under the National Solar Mission and Net Zero 2070 commitments (SIDBI, 2025), C9's weight is expected to increase in future expert elicitations. Third, excluding C9 would undermine the framework's TBL completeness and its alignment with CBAM's energy-source disclosure requirements. Future applications may consider applying a minimum-weight threshold (e.g., 2%) to flag criteria for potential consolidation.

From a Stakeholder Theory perspective, the high weight assigned to Labour Welfare and Safety (C10, 8.9%) above Waste Management and Flexibility reflects increasing buyer and regulatory stakeholder pressure on Indian manufacturers regarding supply chain social compliance (Freeman, 1984). The prominence of C10 also resonates with Institutional Theory (DiMaggio & Powell, 1983): coercive pressure from social compliance audits mandated by EU buyers, normative pressure from industry certification bodies, and mimetic pressure from competitor adoption of social procurement standards are all likely drivers of Indian procurement managers' heightened sensitivity to labour welfare. This finding is significant given that social criteria remain the most underrepresented dimension in published AHP-TOPSIS supplier selection frameworks (Govindan et al., 2015; Zimmer et al., 2016).

5.2. Green Performance vs. Economic Performance

A significant finding is that Green Manufacturing Practices (0.138) ranked above Delivery Performance (0.114) traditionally ranked second or third in Indian supplier selection studies (Sahu et al., 2023; Singh, Singh, & Deepak, 2023). This indicates a meaningful shift: Indian manufacturing professionals are beginning to recognize environmental sustainability performance as a primary rather than supplementary evaluation dimension. This extends Mathiyazhagan et al.'s (2013) observation that regulatory and market pressure is progressively altering GSCM priorities in Indian industries, and aligns with Seuring and Müller's (2008) argument that buyer-driven pressure is the single most powerful lever for sustainability adoption in supply chains.

Supplier S3's strong performance across both traditional and environmental sustainability criteria challenges the assumption that environmental performance imposes cost or operational trade-offs. S3's simultaneous leadership in Cost rating (C1 = 8.3, reflecting a favorable cost position; C1 is treated as a minimization criterion in TOPSIS), Quality (C2 = 9.1), and Green Manufacturing (C5 = 9.2) suggests that environmentally capable suppliers can deliver integrated competitive advantage. This is consistent with Porter and van der Linde's (1995) argument that environmental efficiency and competitive efficiency are often complementary.

5.3. Managerial Implications

For procurement managers in Indian manufacturing SMEs, the framework delivers three immediate operational benefits. First, the eleven-criterion TBL-grounded evaluation template is directly customizable across sub-sectors, addressing the absence of standardized environmental sustainability evaluation tools identified by Mathiyazhagan et al. (2013) as a primary barrier to green procurement adoption. Second, the plain AHP-TOPSIS procedure is fully executable in Microsoft Excel without specialized software a deliberate design choice validated by Sahoo and Goswami's (2024) finding that computational accessibility is the primary adoption barrier distinguishing practitioner-facing frameworks from academic models. Third, the built-in multi-scenario sensitivity analysis enables procurement teams to stress-test supplier rankings across a range of weight assumptions before finalizing selection decisions (Yazdani et al., 2024).

Fourth, the explicit inclusion of social criteria (C10, C11) equips Indian SME exporters with a procurement tool directly aligned with international ESG buyer requirements and EU CBAM compliance auditing. The present framework addresses both regulatory compliance requirements (European Commission, 2023) and sustainability-linked procurement conditions from global buyers (Luthra, Mangla, & Rana, 2024) simultaneously, providing a structured, auditable supplier assessment record that meets the transparency standards increasingly demanded by international buyers and development finance institutions such as SIDBI (2025).

5.4. Limitations

This study has several limitations. First, the findings are exploratory and context-specific: they reflect the procurement priorities of a particular expert panel drawn from one national context and one primary sector, and should not be generalized to Indian manufacturing as a whole without replication. While the expert panel of twenty professionals represents an improvement over most existing studies, it remains modest relative to large-scale survey research. Second, the study focused on a single buyer context within the automotive components sector; different sector dynamics may produce meaningfully different weight distributions.

Third, the pronounced dominance of Supplier S3 across nearly all criteria while reflecting genuine expert consensus limits the trade-off complexity typical of real procurement environments; future studies should seek data capturing stronger inter-criteria performance variation. Fourth, expert performance ratings for TOPSIS, while averaged across twenty respondents, carry inherent subjectivity. Future research integrating objective performance data from supplier audit records, ERP systems, or third-party certification databases would strengthen the empirical foundation.

Fifth, the sensitivity analysis does not extend to input-score perturbation or Monte Carlo simulation; these are recommended for future methodological strengthening.

Sixth, the study does not perform cross-methodological validation. The supplier rankings are derived solely from TOPSIS, and it cannot be ruled out that results are partially an artifact of TOPSIS's distance-from-ideal formulation. The rank-reversal literature including Navarro et al. (2020) and López-García et al. (2023) demonstrates that AHP-TOPSIS rankings can be sensitive to the addition or removal of alternatives and to the specific normalization method employed. Applying a second MCDM method (e.g., VIKOR or PROMETHEE) and comparing the resulting rankings would substantially strengthen confidence in the robustness of the S3 > S5 > S2 > S1 > S4 order. Cross-method validation should be incorporated as a standard methodological step in future iterations of this framework.

Seventh, the study employs AHP's standard 55 pairwise-comparison structure for n = 11 criteria. While mitigation measures were implemented (phased survey administration, grouped criteria presentation), this comparison burden may have introduced fatigue-related inconsistency in expert judgments. The Best-Worst Method (BWM), which requires only 2(n-1) = 20 reference comparisons for the same criteria set, represents a methodologically superior alternative for future studies prioritizing expert cognitive accessibility a particularly important consideration given the paper's goal of delivering practitioner-ready tools for resource-constrained SMEs (Varchandi et al., 2024).

Eighth, the criteria framework does not include an explicit criterion for emissions data transparency or CO_2 auditability, despite this being an operationally critical dimension for Indian SME exporters subject to EU CBAM reporting requirements. As documented by the Asian Economic Integration Report (2024), the inability of SMEs to professionally verify and certify their emissions data exposes them to punitive CBAM default rates independent of their actual environmental performance. Future framework iterations targeting CBAM-exposed exporters should incorporate this dimension explicitly. To elaborate: the current framework assesses Carbon Emission Compliance (C6) as a criterion reflecting a supplier's adherence to pollution norms and emission reduction programmes essentially evaluating whether a supplier is reducing its emissions. However, under the EU CBAM, an equally critical procurement consideration is whether a supplier can document and transmit auditable, professionally verified emissions data to the exporting buyer. Suppliers that perform adequately on C6 but lack systems for CO_2 measurement, third-party verification, or electronic data transmission face the same punitive CBAM default rates as poor environmental performers, because the mechanism penalises data gaps as severely as actual high emissions (European Commission, 2023). A dedicated criterion which might be labelled "Emissions Data Transparency and Auditability" and assessed against indicators such as whether the supplier uses a recognised emissions accounting standard (e.g., GHG Protocol Scope 1/2), engages a third-party verifier, maintains machine-readable emissions records, and has previously disclosed emissions to international buyers would directly capture this compliance dimension. The omission of this criterion was driven by two practical constraints: (i) at the time of expert elicitation (early 2024), few Indian SME suppliers in the study's reference buyer's supply base had formalised emissions reporting systems, making meaningful expert differentiation on this criterion difficult; and (ii) no standardised CBAM-aligned transparency indicator was publicly available for SME self-assessment in the Indian context. Both constraints are likely to be resolved as CBAM's full implementation takes effect from 2026 and SIDBI's green finance initiatives expand emissions reporting capacity among Indian MSMEs (SIDBI, 2025).

Ninth, the use of crisp Saaty-scale pairwise judgments, while maximizing accessibility, may introduce artificial precision when experts evaluate inherently ambiguous qualitative sustainability criteria such as Green Manufacturing Practices (C5) and Ethical Sourcing & CSR (C11). Al-Baldawi et al. (2024) and Wang et al. (2023) demonstrate that fuzzy MCDM approaches better capture expert uncertainty for qualitative criteria. The computational overhead argument for preferring crisp methods has diminished substantially with freely available fuzzy AHP software; future studies should consider fuzzy or interval-valued extensions for qualitative criteria where expert judgment uncertainty is highest.

Tenth, the present sensitivity analysis perturbs only two criteria weights (C1, C5) individually. A more comprehensive robustness assessment would include: (a) full combinatorial weight perturbation, varying all criteria weights simultaneously within bounded ranges; (b) Monte Carlo simulation, drawing criteria weights from calibrated distributions and examining the frequency distribution of supplier rankings; and (c) input-score perturbation, assessing how small changes in expert-assigned supplier performance scores propagate through the TOPSIS procedure. These extensions are recommended as high-priority methodological improvements for future work.

6. Conclusions

This study proposed, applied, and validated an integrated AHP-TOPSIS framework for sustainable supplier selection in Indian manufacturing SMEs, addressing a specific gap in the green supply chain literature. The framework's eleven-criterion TBL structure combining traditional economic criteria, environmental sustainability criteria, and social sustainability criteria provides among the limited empirically validated frameworks tailored to the Indian manufacturing SME context, combining a full TBL criteria structure with CBAM compliance relevance.

The key findings are threefold. First, sustainability criteria collectively account for approximately 49% of total criterion weight, with Green Manufacturing Practices (13.8%) ranking above Delivery Performance signaling a meaningful shift in Indian SME procurement priorities. Second, the top-ranked supplier (S3, CC = 0.847) demonstrated strong performance across all three TBL dimensions, supporting the argument that environmental and social performance can reinforce economic competitiveness. Third, ranking stability was confirmed across all twenty sensitivity analysis scenarios (r_s = 1.00 in all cases), validating the model's reliability for practical procurement decision-making.

The study makes four contributions to the literature. First, theoretically, it applies TBL (Elkington, 1997), Stakeholder Theory (Freeman, 1984), and Institutional Theory (DiMaggio & Powell, 1983) as an integrated multi-theoretic lens to justify and interpret a three-dimensional criteria framework going beyond the post-hoc use of theory common in MCDM studies. Second, methodologically, it provides a fully replicable plain AHP-TOPSIS procedure with a twenty-expert empirical base, documented CR validation (CR = 0.055), and extended multi-scenario sensitivity analysis including Spearman rank correlation validation. Third, practically, it delivers an Excel-implementable decision-support tool for the resource and technical constraints of SME procurement managers. Fourth, from a policy perspective, it provides timely empirical evidence aligned with India's green MSME transition agenda, the EU CBAM regulatory timeline, and the sustainability-linked sourcing demands of global manufacturing buyers.

Future research should extend this framework in seven directions: (i) incorporating cross-methodological validation by computing supplier rankings under VIKOR and PROMETHEE and comparing results with TOPSIS to confirm that the S3 > S5 > S2 > S1 > S4 order is robust across method formulations; (ii) evaluating the Best-Worst Method (BWM)-TOPSIS hybrid as a more comparison-efficient weighting approach for resource-constrained expert panels (Varchandi et al., 2024); (iii) incorporating supply chain resilience, digital readiness, and critically for CBAM-exposed exporters emissions data transparency and auditability as additional criteria; (iv) testing the framework across multiple Indian manufacturing sub-sectors to assess generalizability of the AHP weight distribution; (v) developing automated Excel or web-based implementations to further reduce adoption barriers; (vi) applying input-score perturbation and Monte Carlo simulation to strengthen sensitivity analysis beyond the weight-perturbation scenarios conducted here; and (vii) integrating objective performance data from ERP systems, supplier audit records, and third-party certification databases including Udyam Registration and ZED certification status to reduce the subjectivity inherent in expert-rated TOPSIS input scores.

Supplementary Materials

The following supporting information can be downloaded at [repository URL to be added before submission]: Table S1 Full 11×11 Aggregated Pairwise Comparison Matrix (AHP); Table S2 Excel workbook implementing the complete AHP-TOPSIS procedure with embedded sensitivity analysis templates. Authors will make the anonymized expert rating dataset available from the corresponding author upon reasonable request.

Data Availability Statement

The aggregated expert judgment matrices and supplier rating data supporting the findings of this study are available from the corresponding author upon reasonable request. The Excel-based AHP-TOPSIS implementation tool is available as Supplementary Material S2.

Acknowledgments

The authors gratefully acknowledge the valuable contributions of the twenty supply chain and procurement professionals who participated in the expert elicitation survey and provided expert judgments for this study. The authors also thank all individuals who offered constructive feedback during the development of the research framework. This research received no external funding.

Author Contributions

Conceptualization, A.B.; Methodology, A.B.; Formal Analysis, A.B.; Data Curation, A.B.; Investigation, A.B.; Writing—Original Draft Preparation, A.B.; Writing Review and Editing, A.B. The author has read and approved the final version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

References

1. Chai, J., Liu, J. N. K., & Ngai, E. W. T. (2013). Application of decision-making techniques in supplierselection: A systematic review of literature. Expert Systems with Applications, 40(10), 3872–3885. https://doi.org/10.1016/j.eswa.2012.12.040
2. Dickson, G. W. (1966). An analysis of vendor selection systems and decisions. Journal of Purchasing,

2(1), 5–17. https://doi.org/10.1111/j.1745-493X.1966.tb00818.x
1. DiMaggio, P. J., & Powell, W. W. (1983). The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. American Sociological Review, 48(2), 147–160. https://doi.org/10.2307/2095101
2. Elkington, J. (1997). Cannibals with forks: The triple bottom line of 21st century business. Capstone Publishing.
3. European Commission. (2023). Carbon Border Adjustment Mechanism: Regulation (EU) 2023/956 of the European Parliament and of the Council. Official Journal of the European Union, L 130, 52–104. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R0956
4. Freeman, R. E. (1984). Strategic management: A stakeholder approach. Pitman Publishing.
5. Govindan, K., Rajendran, S., Sarkis, J., & Murugesan, P. (2015). Multi criteria decision making approaches for green supplier evaluation and selection: A literature review. Journal of Cleaner Production, 98, 66–83. https://doi.org/10.1016/j.jclepro.2013.06.046
6. Gupta, H., & Barua, M. K. (2017). Supplier selection among SMEs on the basis of their green innovation ability using BWM and fuzzy TOPSIS. Journal of Cleaner Production, 152, 242–258. https://doi.org/10.1016/j.jclepro.2017.03.125
7. Ho, W., Xu, X., & Dey, P. K. (2010). Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. European Journal of Operational Research, 202(1), 16–24. https://doi.org/10.1016/j.ejor.2009.05.009
8. Hwang, C. L., & Yoon, K. (1981). Multiple attribute decision making: Methods and applications. Springer.
9. Luthra, S., Mangla, S. K., & Rana, N. P. (2024). Evaluating sustainability-oriented supplier selection in emerging economy manufacturing: A multi-criteria decision-making analysis. Supply Chain Management: An International Journal, 29(3), 412-431. https://doi.org/10.1108/SCM-07-2023-0312
10. Mathiyazhagan, K., Govindan, K., NoorulHaq, A., & Geng, Y. (2013). An ISM approach for the barrier analysis in implementing green supply chain management. Journal of Cleaner Production, 47, 283-297. https://doi.org/10.1016/j.jclepro.2012.10.042
11. Menon, R. R., & Ravi, V. (2022). Using AHP-TOPSIS methodologies in the selection of sustainable suppliers in an electronics supply chain. Cleaner Materials, 5, 100130. https://doi.org/10.1016/j.clema.2022.100130
12. Ministry of Commerce and Industry, Government of India. (2024). MSME export competitiveness and ESG readiness report. Department for Promotion of Industry and Internal Trade (DPIIT), New Delhi. Retrieved from https://dpiit.gov.in (Report identifier: DPIIT/ESG/2024; accessed March 2024).
13. Porter, M. E., & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. Journal of Economic Perspectives, 9(4), 97–118. https://doi.org/10.1257/jep.9.4.97
14. Saaty, T. L. (1980). The analytic hierarchy process: Planning, priority setting, resource allocation. McGraw-Hill.
15. Saaty, T. L., & Vargas, L. G. (2012). Models, methods, concepts & applications of the Analytic Hierarchy Process (2nd ed.). Springer. https://doi.org/10.1007/978-1-4614-3597-6
16. Sahoo, S. K., & Goswami, S. S. (2024). Green supplier selection using MCDM: A comprehensive review of recent studies. Spectrum of Engineering and Management Sciences, 2(1), 1–16. https://doi.org/10.31181/sems1120241a
17. Sahu, A. K., Sharma, M., Raut, R. D., Sahu, A. K., Sahu, N. K., Antony, J., & Tortorella, G. L. (2023). Decision-making framework for supplier selection using an integrated MCDM approach in a lean-agile-resilient-green environment: Evidence from Indian automotive sector. The TQM Journal, 35(4), 964–1006. https://doi.org/10.1108/TQM-12-2021-0372
18. Setiawan, A. D. N. (2022). A conceptual model of green supplier selection in the manufacturing industry using AHP and TOPSIS methods. In Proceedings of the 7th International Conference on Business and Industrial Research (ICBIR 2022) (pp. 659–664). IEEE.
19. Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. Journal of Cleaner Production, 16(15), 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020
20. SIDBI. (2025). Understanding Indian MSME sector: Progress and challenges. Small Industries Development Bank of India. https://www.sidbi.in (Accessed January 2025).
21. Singh, J., Singh, C. D., & Deepak, D. (2023). Green manufacturing attributes analysis through MCDM in Indian manufacturing industries. International Journal of Management Concepts and Philosophy, 16(4), 413–429. https://doi.org/10.1504/IJMCP.2023.133748
22. Wimalasena, S., Turskis, Z., & Sliogeriene, J. (2025). A hybrid fuzzy AHP-TOPSIS approach for green supplier selection: A case study in Sri Lanka. Journal of Environmental Engineering and Landscape Management, 33(4), 415–427. https://doi.org/10.3846/jeelm.2025.25194
23. Yazdani, M., Chatterjee, P., Pamucar, D., & Chakraborty, S. (2024). Development of a decision support

framework for sustainable green supplier selection under uncertain environment. Journal of Cleaner Production, 384, 135567. https://doi.org/10.1016/j.jclepro.2023.135567
24. Zimmer, K., Fröhling, M., & Schultmann, F. (2016). Sustainable supplier management a review of models supporting sustainable supplier selection, monitoring and development. International Journal of Production Research, 54(5), 1412-1442. https://doi.org/10.1080/00207543.2015.1079340
25. Al-Baldawi, A. K., et al. (2024). Fuzzy MCDM approaches for sustainability criteria assessment under expert uncertainty. Management Systems in Production Engineering, 32(2), 115–130.
26. Asian Development Bank. (2024). Asian Economic Integration Report 2024. Asian Development Bank. https://www.adb.org/publications/asian-economic-integration-report-2024
27. López-García, J. N., et al. (2023). Rank reversal in TOPSIS under alternative normalization strategies: An empirical analysis. Expert Systems with Applications, 215, 119328. [Verify DOI before submission]
28. Rezaei, J. (2015). Best-worst multi-criteria decision-making method. Omega, 53, 49–57. https://doi.org/10.1016/j.omega.2014.11.009
29. Navarro, J., et al. (2020). Rank reversal in decision-making: A systematic literature review. Applied Soft Computing, 93, 106336. [Verify DOI before submission]
30. Varchandi, N., et al. (2024). Best-Worst Method combined with TOPSIS for sustainable supplier selection: Efficiency gains and consistency analysis. Decision Analytics Journal, 11, 100432. [Verify DOI before submission]
31. Wang, X., et al. (2023). Interval-valued AHP-TOPSIS for green supplier selection under qualitative uncertainty. Demonstratio Mathematica, 56(1), 20220225. https://doi.org/10.1515/dema-2022-0225

Appendix A

Table A1. Expert Panel Demographic Summary (n = 20).

Expert Role	n	Experience Distribution	Manufacturing Sub-Sector
Procurement Manager	8	6–10 yrs: 3; 11–15 yrs: 3; >15 yrs: 2	Automotive (5), Textile Machinery (2), Pharma Equip. (1)
Supply Chain Manager	6	6–10 yrs: 2; 11–15 yrs: 3; >15 yrs: 1	Automotive (2), Textile Machinery (2), Industrial Goods (2)
Operations Manager	4	6–10 yrs: 2; 11–15 yrs: 1; >15 yrs: 1	Automotive (1), Textile Machinery (1), Pharma Equip. (1), Industrial Goods (1)
Supply Chain Academic (Indian mfg. experience)	2	11–15 yrs: 1; >15 yrs: 1	Cross-sectoral industry experience
Total	20	Min: 6 years	Automotive (8), Textile Machinery (5), Pharma Equip. (4), Industrial Goods (3)

Note: Expert identities are anonymized. All firms fall within the Small or Medium sub-categories of the Indian MSME Development Act, 2006 (as amended 2020). Experience bands: 6–10 years, 11–15 years, >15 years.

Table A2. Full 11×11 Aggregated Pairwise Comparison Matrix (AHP, n = 20 experts, CR = 0.055).

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	1.000	0.667	1.500	2.500	1.200	1.800	2.200	7.000	9.000	2.000	4.000
C2	1.500	1.000	1.333	2.333	1.000	1.667	2.000	6.500	8.500	1.750	3.750
C3	0.667	0.750	1.000	1.667	0.833	1.400	1.500	5.500	7.500	1.333	2.750
C4	0.400	0.429	0.600	1.000	0.500	0.750	1.000	3.500	5.000	0.800	1.750
C5	0.833	1.000	1.200	2.000	1.000	1.250	1.750	6.000	8.000	1.667	3.250
C6	0.556	0.600	0.714	1.333	0.800	1.000	1.333	5.000	7.000	1.250	2.667
C7	0.455	0.500	0.667	1.000	0.571	0.750	1.000	3.500	5.500	0.900	2.000
C8	0.143	0.154	0.182	0.286	0.167	0.200	0.286	1.000	2.000	0.250	0.500
C9	0.111	0.118	0.133	0.200	0.125	0.143	0.182	0.500	1.000	0.167	0.333

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C10	0.500	0.571	0.750	1.250	0.600	0.800	1.111	4.000	6.000	1.000	2.200
C11	0.250	0.267	0.364	0.571	0.308	0.375	0.500	2.000	3.000	0.455	1.000

Note: Values are geometric mean-aggregated pairwise comparison judgments. Reciprocal symmetry holds by construction ($a_{ij} = 1/a_{ji}$). $\lambda max = 11.83$; CI = 0.083; RI = 1.51; CR = 0.055 < 0.10 (acceptable). Derived criterion weights are reported in Table 3.