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Article

Evaluating Sustainability Aspects Through Strategic Dimensions of Circular Economy in India's Electronics Industry: An Integrated Fuzzy MCDM Approach

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Abstract: *The rapid growth of the electronics industry in India has led to increasing e-waste challenges. This has resulted in sustainability concerns as a huge amount of this waste is handled by the informal sector without appropriate knowledge of its disposal. Transition towards circular economy (CE) is thus imperative to address these issues. This study seeks to identify and evaluate the strategic dimensions of CE implementation in India's electronics sector with respect to five key sustainability aspects: environmental, social, economic, governance, and cultural. Linguistic responses collected from industry/academia experts via a structured questionnaire were analysed using a Pythagorean fuzzy (PF)-integrated multi-criteria decision-making (MCDM) approach. To derive the objective weights of 22 strategic dimensions, the PF-CRITIC (CRiteria Importance Through Intercriteria Correlation) technique was applied. Thereafter, the PF-CoCoSo (Combined Compromise Solution) method was used along with the derived weights to rank the five sustainability aspects, thereby highlighting the aspects most strongly influenced by the strategic dimensions of CE adoption. Environmental sustainability was ranked highest, followed by governance, economic, social, and cultural aspects. The CRITIC weights showed moderate variation, with collection access, market incentives, and awareness exhibiting relatively higher objective weights within the decision matrix. A sensitivity analysis was conducted to assess the reliability and stability of the results. The findings provide a relative positioning of sustainability priorities and offer practical guidance for translating CE strategies into action. Specifically, policymakers and industry stakeholders can use the identified priorities to strengthen CE initiatives, thereby supporting a more focused circular transition in India's electronics sector.*

Keywords: *Circular economy; Sustainability; Strategic dimensions; Electronics; MCDM*

1. Introduction

Over the past five decades, the global population has doubled, while material extraction and primary energy production have more than tripled. Meanwhile, the global economy has grown nearly fivefold and international trade tenfold, intensifying pressures on the environment (Gümüş & Kaya, 2026). The electronics industry is an important part of economic growth, especially in emerging economies worldwide. However, this advancement is accompanied by serious sustainability concerns due to mounting e-waste levels (Murthy & Ramakrishna, 2022; Pollard et al., 2021). In India, the sector has witnessed substantial growth in both production and consumption, especially in consumer electronics. This can be attributed to rising population and income levels along with changing lifestyles (Islam et al., 2021). Nevertheless, inappropriate handling and disposal of e-waste have increased concerns related to public well-being, environmental pollution and resource depletion (Murthy & Ramakrishna, 2022).

All these factors together hinder efforts towards sustainable development (Ali & Shirazi, 2023; Rajesh et al., 2022). To address these challenges, a transformation from the traditional linear 'take-make-dispose' model to a circular economy (CE) model has been widely accepted as a viable solution (Zoka & Korez Vide, 2025).

CE practices facilitate efficient resource utilization and value retention by minimizing waste and ensuring extended product life cycles (Lieder & Rashid, 2016). Hence, the CE approach is considered instrumental in attaining the United Nations Sustainable Development Goals (SDGs) (A. Kumar et al., 2022). Previous studies have emphasized the need for designing strategic interventions for effective CE implementation in India's electronics industry in order to ensure sustainable development in the sector (Arya & Kumar, 2020). This research thus seeks to identify and evaluate the relative contribution of strategic dimensions that support CE implementation in India's electronics sector and to assess the relative positioning of five sustainability aspects under these strategic dimensions.

An extensive literature review validated by industry/academia experts is used to identify 22 strategic dimensions of CE implementation in India's electronics sector. These dimensions are mapped to five key sustainability aspects, namely environmental, social, economic, governance, and cultural sustainability, to develop a structured questionnaire. Linguistic responses obtained from the experts are analysed using a Pythagorean fuzzy (PF)-integrated multi-criteria decision-making (MCDM) approach. This study employs the CRiteria Importance Through Intercriteria Correlation (CRITIC) technique to derive objective weights of each strategic dimension. Further, the Combined Compromise Solution (CoCoSo) method is applied to obtain rankings of the different sustainability aspects based on their aggregated evaluations across the strategic dimensions.

Several prior works use Interpretive Structural Modeling (ISM), Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC), Decision Making Trial and Evaluation Laboratory (DEMATEL), Best-Worst Method (BWM), Stepwise Weight Assessment Ratio Analysis (SWARA), Weighted Aggregated Sum Product Assessment (WASPAS), or fuzzy methods to rank barriers or factors (Debnath et al., 2023; Jaiswal & Mukti, 2025; Mahanth et al., 2023). Although fuzzy MCDM approaches are increasingly used in sustainability and CE research, the methodological contribution of this study extends beyond combining existing techniques. The PF-based CRITIC–CoCoSo framework is well suited to the problem: the PF environment captures uncertainty and hesitation in linguistic expert evaluations, CRITIC objectively determines criterion weights from contrast intensity and inter-criterion relationships, and CoCoSo integrates additive and multiplicative perspectives to derive a compromise ranking of sustainability aspects. Together, these methods enable a systematic evaluation of CE strategic dimensions without requiring experts to assign subjective importance weights to individual criteria.

The literature offers limited insight into how a comprehensive set of CE implementation strategies collectively contributes to different sustainability dimensions in India's rapidly growing electronics industry. Existing studies largely examine e-waste management, recycling, reverse logistics, extended producer responsibility (EPR), consumer behaviour, and technological interventions separately, leaving a need for an integrated framework that evaluates CE strategies across environmental, social, economic, governance, and cultural dimensions. Addressing this gap is particularly important in India, where rising electronics consumption is accompanied by collection and recycling constraints, informal-sector participation, evolving regulations, and the need for stronger stakeholder coordination. Accordingly, the study goes beyond ranking sustainability aspects by examining the relative contribution of 22 CE strategic dimensions and identifying the sustainability areas most strongly supported by them. It further translates these findings into stakeholder-specific actions, helping policymakers, manufacturers, recyclers, informal-sector actors, consumers, and other stakeholders identify where greater attention and coordination are needed to advance CE implementation.

2. Materials and methods

The study integrates exploratory research with a quantitative decision-making framework to identify CE strategic dimensions, evaluate their relative contribution, and rank the sustainability aspects based on their aggregated evaluations across these strategic dimensions. The overall methodological framework adopted in this study is illustrated in Figure 1. It presents the sequential stages from

identification and expert validation of the CE strategic dimensions to PF-based evaluation, objective weighting through CRITIC, ranking of sustainability aspects using CoCoSo, and sensitivity analysis of the obtained results.

The questionnaire was developed through a sequential literature review and expert validation process. An extensive review first identified an initial set of strategic dimensions for CE implementation in India's electronics sector. Relevant studies were collected from databases such as Google Scholar, Scopus, Web of Science, and ScienceDirect using keywords including "circular economy", "electronics industry", "strategies," "solutions," and "techniques". The screening process excluded duplicate entries, non-English publications, conference abstracts, editorials, and studies lacking direct relevance to the study. To avoid repetition, strategic dimensions with comparable meanings or definitions were grouped together. The expert panel qualitatively assessed the literature-derived strategic dimensions for content validity before the final decision matrix was developed. Experts assessed these dimensions for their relevance and applicability to the Indian context, leading to the removal of less relevant dimensions and the consolidation of conceptually overlapping ones. The resulting 22 dimensions formed the final decision criteria and were evaluated against five sustainability aspects (identified through the literature): environmental, social, economic, governance, and cultural. These strategic dimensions and aspects were subsequently incorporated into the structured questionnaire. As the questionnaire served as an expert MCDM evaluation matrix rather than a psychometric scale, separate scale-validation procedures were not conducted. The 22 CE strategic dimensions were treated as the decision criteria (S1–S22), while the five sustainability aspects were treated as the alternatives (A1–A5) in the MCDM framework. This structure allows each sustainability aspect to be evaluated against the same set of CE strategic dimensions. CRITIC was used to derive objective criterion weights based on variability and inter-criterion relationships in the decision matrix, while CoCoSo combined the weighted evaluations to rank the five sustainability aspects. Strategic dimensions and sustainability aspects, along with their descriptions and supporting references from literature, are presented in Tables 1 and 2, respectively. Table 1 also maps the 22 strategic dimensions to the CE/value-chain stages with which they are most directly associated. The mapping covers design, production, distribution/use, collection, reverse logistics, and product and material recovery. Several dimensions related to regulation, stakeholder cooperation, finance, monitoring, and workforce capabilities operate across multiple stages and are therefore identified as cross-cutting enablers.

The study used purposive sampling to select five experts—four senior industry professionals and one academic—thereby combining practical and theoretical perspectives. Small expert panels of 3–6 carefully selected members are common in PF and linguistic MCDM studies, where the emphasis is on relevant expertise rather than panel size (Abdullah & Goh, 2019). Such panels typically involve experienced professionals capable of providing informed judgements on the decision problem (Wu et al., 2016). Consistent with this approach, all experts in the present study had more than 25 years of experience in their respective fields.

The industry experts were selected for their direct involvement in key electronics industry functions and their complementary expertise in sustainability and CE practices. To ensure diverse functional perspectives, they represented engineering, delivery, quality/waste management, and program management. Suitable experts were identified by contacting senior managers and department heads from organizations affiliated with the India Cellular & Electronics Association (ICEA). 'India Cellular & Electronics Association (ICEA) is an apex body representing India's electronics sector' (India Cellular and Electronics Association, n.d.). The academic expert complemented these industry perspectives with relevant theoretical and research expertise. Table 3 summarizes the profiles and expertise of the expert panel.

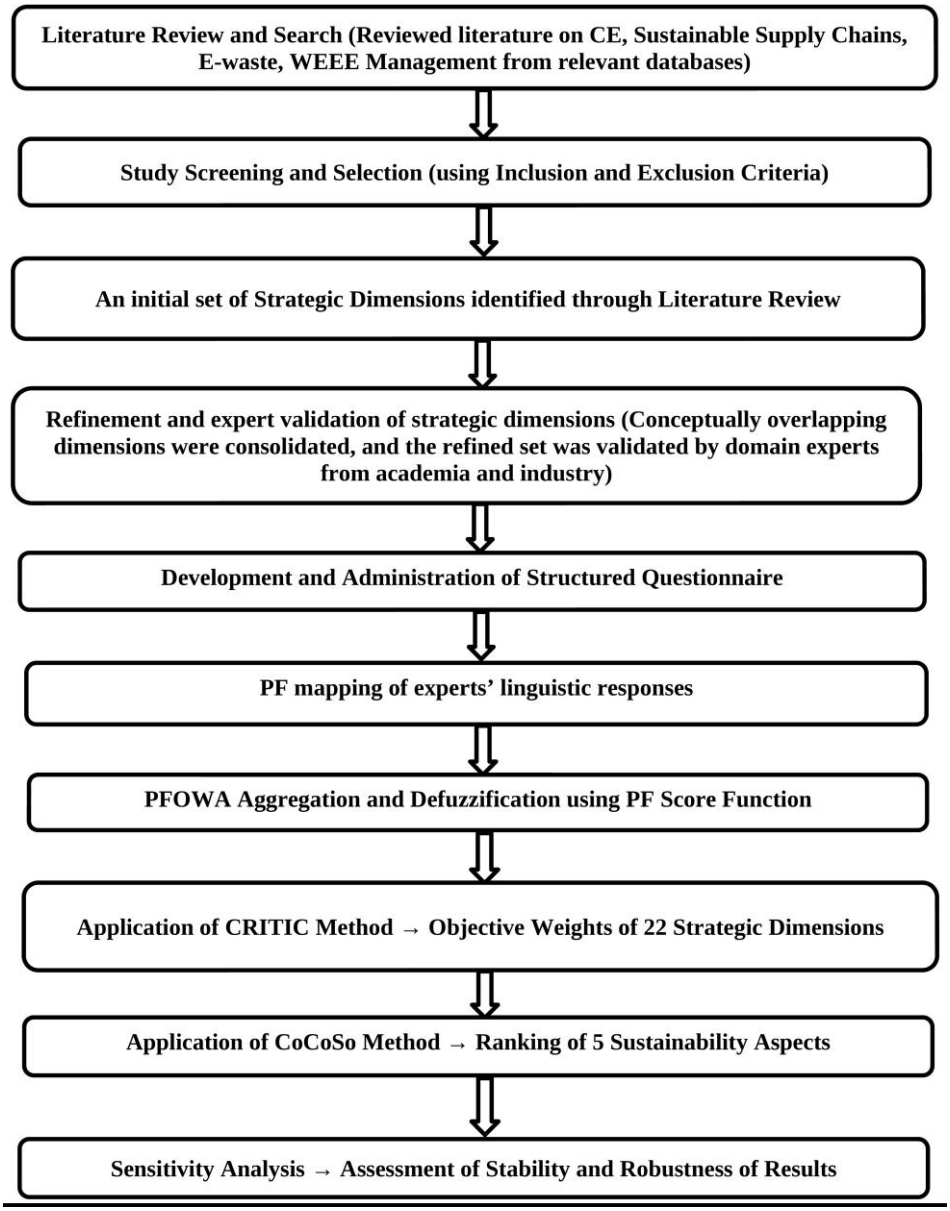


Figure 1. Methodological framework adopted in the study

Note: CE – circular economy; WEEE – waste electrical and electronic equipment; PF – Pythagorean fuzzy; PFOWA – Pythagorean fuzzy ordered weighted averaging; CRITIC – CRiteria Importance Through Intercriteria Correlation; CoCoSo – Combined Compromise Solution.

Table 1. Strategic dimensions of CE adoption in the Indian electronics industry and their mapping to CE/value-chain stages

Label	Strategic dimensions	Description	Reference(s)	CE/value-chain stage(s)
S1	Adaptive legislation and evidence-based recycling policies	This promotes flexible and fact-based regulations for safe collection, reuse, recycling, and disposal of discarded electronic products.	(Arya & Kumar, 2020; Dada et al., 2025; Murthy & Ramakrishna, 2022; Pan et al., 2022)	Collection; Product and Material Recovery; Cross-cutting Regulatory Enabler

Label	Strategic dimensions	Description	Reference(s)	CE/value-chain stage(s)
S2	Resource-efficient 10R strategy	This promotes resource efficiency through practices such as refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover.	(Gaur et al., 2024; Jaiswal & Mukti, 2024; Pan et al., 2022)	Design; Production; Distribution/Use; Product and Material Recovery
S3	Sustainable product design	It focuses on designing electronic products with recyclable materials and easy disassembly features to improve recycling efficiency, extend product lifespan, and reduce waste generation.	(Arya & Kumar, 2020; Pan et al., 2022; Srivastav et al., 2023)	Design; Product and Material Recovery
S4	Structured reverse logistics infrastructure	It promotes organized systems for efficient collection, transportation, processing, and recycling of discarded electronic products through structured recovery networks.	(Arya & Kumar, 2020; Mallick et al., 2023; Pan et al., 2022)	Collection; Reverse Logistics; Product and Material Recovery
S5	Public awareness	This promotes awareness campaigns that encourage responsible disposal practices, informed choices, and environmentally sustainable consumer behaviour.	(Arya & Kumar, 2020; Islam et al., 2021; A. Kumar & Dixit, 2018; Puzzo & Prati, 2024)	Distribution/Use; Collection
S6	Collaborative integration of formal and informal e-waste sectors	It encourages role-based collaboration between formal and informal sectors through community organizations and NGOs to strengthen collection and recycling systems.	(Ahirwar & Tripathi, 2021; Arya & Kumar, 2020; Gollakota et al., 2020; Murthy & Ramakrishna, 2022)	Collection; Reverse Logistics; Product and Material Recovery
S7	Easily accessible e-waste collection centres	This focuses on establishing convenient and widely available collection points to encourage proper disposal of e-waste.	(Arya & Kumar, 2020; Mallick et al., 2023; Murthy & Ramakrishna, 2022)	Collection
S8	Responsible recycling practices	This supports safe, ethical, and sustainable recycling processes.	(Ádám et al., 2021; Smith & Behdad, 2025)	Product and Material Recovery
S9	Strengthening EPR compliance	It emphasizes producer accountability in collecting, recycling, and managing end-of-life electronic products to improve recycling efficiency and environmental sustainability.	(Arya & Kumar, 2020; Gaur et al., 2025; Murthy & Ramakrishna, 2022; Pan et al., 2022)	Collection; Reverse Logistics; Product and Material Recovery; Cross-cutting Regulatory Enabler

Label	Strategic dimensions	Description	Reference(s)	CE/value-chain stage(s)
S10	Economic reward systems	This promotes public participation in recycling through monetary rewards, free transportation, and exchange-based benefits.	(Jaiswal & Mukti, 2024; Puzzo & Prati, 2024)	Distribution/Use; Collection
S11	Servitized/product-service models	This promotes leasing, pay-per-use, and result-oriented business models that retain ownership with Original Equipment Manufacturer (OEM), enabling efficient product take-back, reuse, and recycling.	(Fernandes et al., 2020; Han et al., 2020; Pieroni et al., 2019)	Distribution/Use; Collection; Reverse Logistics; Product and Material Recovery
S12	Integrated stakeholder cooperation	It encourages collaboration among governments, businesses, scientists, and recycling professionals to promote sustainable product design, effective policies, and responsible waste management.	(Arya & Kumar, 2020; Gaur et al., 2025; Murthy & Ramakrishna, 2022)	Design; Collection; Product and Material Recovery; Cross-cutting Coordination Enabler
S13	Technology-driven innovations	This promotes the use of Artificial Intelligence, robotics, automated disassembly, and advanced sorting technologies to improve the efficiency, accuracy, and sustainability of collection and recycling processes.	(Gaur et al., 2025; Golpeo et al., 2025; Murthy & Ramakrishna, 2022; Shahabuddin et al., 2023)	Collection; Product and Material Recovery
S14	Circular value marketing	This focuses on integrating sustainability practices into brand identity to strengthen consumer confidence, reputation, and long-term brand value.	(Chamberlin & Boks, 2018; Nag et al., 2021; Urbinati et al., 2017)	Distribution/Use
S15	Life Cycle Assessment (LCA)	It emphasizes the use of LCA to evaluate the environmental impact of a product throughout its entire life cycle.	(Arya & Kumar, 2020; He et al., 2024; Singh et al., 2025; T. Zhang et al., 2024)	Design; Production; Distribution/Use; Collection; Reverse Logistics; Product and Material Recovery
S16	Incorporating Extended Consumer Responsibility (ECR) in regulations	It emphasizes consumer responsibility in the proper disposal and return of electronic products to strengthen sustainable waste management systems.	(Arya & Kumar, 2020; Islam et al., 2021)	Distribution/Use; Collection; Cross-cutting Regulatory Enabler
S17	Knowledge-driven workforce advancement	This focuses on enhancing workers' technical skills in product design, recycling processes, and life cycle cost assessment.	(R. Kumar et al., 2023; Srivastav et al., 2023)	Design; Product and Material Recovery; Cross-cutting Capability Enabler

Label	Strategic dimensions	Description	Reference(s)	CE/value-chain stage(s)
S18	Development of value-added products	This focuses on transforming e-waste residues into useful products such as construction materials and decorative items to promote resource recovery and CE practices.	(Arya & Kumar, 2020)	Production; Product and Material Recovery
S19	Digitally monitored resource recovery system	It supports coordinated digital and physical infrastructure for electronic product coding, online registration, and government-supported recycling systems for transparent and sustainable waste management.	(Liu et al., 2023)	Collection; Reverse Logistics; Product and Material Recovery
S20	Revenue-generating financial strategies	This focuses on implementing eco-taxes, recycling fees, and funding mechanisms like allocating corporate social responsibility (CSR) funds to support e-waste management systems, infrastructure development, and research initiatives.	(Fiksel et al., 2021; Goyal & Gupta, 2024)	Collection; Reverse Logistics; Product and Material Recovery; Cross-cutting Financial Enabler
S21	Cross-border monitoring for e-waste movement	This emphasizes tracking and evaluating cross-border e-waste flows to prevent illegal movement and ensure safe waste management practices.	(Gollakota et al., 2020; Liu et al., 2023; Patil & Ramakrishna, 2020)	Reverse Logistics; Cross-cutting Monitoring/Regulatory Enabler
S22	Research-driven occupational safety framework for workers	It supports focused research and preventive measures to minimize health risks in recycling operations.	(Ádám et al., 2021; Gollakota et al., 2020; Murthy & Ramakrishna, 2022)	Product and Material Recovery; Cross-cutting Workforce/Safety Enabler

Table 2. Description of sustainability aspects

Label	Sustainability aspects	Description	References
A1	Environmental	Reflects the responsible use and conservation of natural resources, prevention and reduction of pollution, and maintenance of ecological balance to ensure that environmental resources remain available for future generations.	(Elleuch et al., 2018; Kaimovs & Skarupins, 2024)
A2	Social	Reflects the long-term well-being and quality of life of people through social equity, inclusion, participation, access to opportunities and resources, and reduction of poverty, inequality, and vulnerability.	(Eizenberg & Jabareen, 2017; Kaimovs & Skarupins, 2024)
A3	Economic	Reflects the capacity to maintain long-term economic stability and growth through efficient resource use, value creation, financial viability,	(Kaimovs & Skarupins, 2024; Tennakoon & Janadari, 2022)

		and responsible economic development without compromising social and environmental well-being.	
A4	Governance	Reflects the institutional and decision-making structures, policies, accountability mechanisms, transparency, stakeholder engagement, and fair operating practices that enable responsible and effective implementation of sustainability initiatives.	(Agrawal et al., 2022; Bennett & Satterfield, 2018; Glass & Newig, 2019)
A5	Cultural	Reflects the capacity of shared values, norms, knowledge, and practices to support adaptation and behavioural transformation towards more sustainable ways of living, thereby strengthening long-term social resilience.	(Järvelä, 2023; Meireis & Rippl, 2018; Zheng et al., 2021)

Table 3. Profile of experts participating in the study

Expert	Representation	Functional/domain expertise	Professional experience
Expert 1	Industry	Engineering	>25 years
Expert 2	Industry	Delivery	>25 years
Expert 3	Industry	Quality/Waste Management	>25 years
Expert 4	Industry	Program Management	>25 years
Expert 5	Academia	Professor, Operations and Supply Chain Management	>25 years

The questionnaire was shared with the experts by email to collect their individual responses. The questionnaire asked respondents to evaluate every strategic dimension on each sustainability aspect using a five-point linguistic scale (i.e., 'Very Low (VL)', 'Low (L)', 'Medium (M)', 'High (H)' and 'Very High (VH)').

Linguistic responses are widely used in multi-criteria decision-making frameworks to better capture human judgements in imprecise and vague settings (Abdullah & Goh, 2019). For quantitative analysis of the linguistic responses, each linguistic term was mapped to a corresponding PF number. Pythagorean fuzzy sets (PFSs) are widely used in multi-criteria selection and ranking problems. Instead of a single numeric value, PFSs capture vagueness by assigning a membership (μ) and non-membership (ν) degree to each linguistic variable in the (μ, ν) format satisfying the PF condition $\mu^2 + \nu^2 \leq 1$ (Peng & Selvachandran, 2019).

Five linguistic matrices, one from each expert, were converted into PF decision matrices using the PF-linguistic mapping shown in Table 4.

Table 4. Pythagorean fuzzy numbers corresponding to linguistic terms

Linguistic term	Abbreviation	Pythagorean fuzzy number
Very Low	VL	(0.1, 0.9)
Low	L	(0.3, 0.8)
Medium	M	(0.5, 0.6)
High	H	(0.7, 0.4)
Very High	VH	(0.9, 0.1)

Source: Adapted from Peng et al. (2020)

Each expert was assigned an equal weight of 0.2 to ensure balanced and unbiased evaluation. Equal weights were assigned because all experts were considered to have comparable levels of knowledge and experience.

The five PF decision matrices were aggregated using the Pythagorean fuzzy ordered weighted averaging (PFOWA) operator proposed by X. Zhang (2016). Let $\beta_j = P\left(\mu_{\beta_j}, \nu_{\beta_j}\right), j = 1,2, \dots, n$, denote a set of Pythagorean fuzzy numbers (PFNs) and w_j denote the corresponding aggregation weights satisfying

$w_j \geq 0$ $(j = 1,2, \dots, n)$ and $\sum_{j=1}^{n} w_j = 1$. After arranging the PFNs according to the ordering specified by the PFOWA operator, the aggregated PFN is obtained using Eq. (1) (X. Zhang, 2016).

$$\boldsymbol{PFOWA}(\boldsymbol{\beta_1}, \boldsymbol{\beta_2}, \dots, \boldsymbol{\beta_n}) = \boldsymbol{w_1}\boldsymbol{\beta}_{\boldsymbol{\sigma(1)}} \oplus \boldsymbol{w_2}\boldsymbol{\beta}_{\boldsymbol{\sigma(2)}} \oplus \dots \oplus \boldsymbol{w_n}\boldsymbol{\beta}_{\boldsymbol{\sigma(n)}} =$$

$$\boldsymbol{P}\left(\sqrt{\boldsymbol{1} - \prod_{\boldsymbol{j=1}}^{\boldsymbol{n}} \left(\boldsymbol{1} - \boldsymbol{\mu}^{\boldsymbol{2}}_{\boldsymbol{\beta}_{\boldsymbol{\sigma(j)}}}\right)^{(\boldsymbol{w_j})}}, \prod_{\boldsymbol{j=1}}^{\boldsymbol{n}} \boldsymbol{\nu}_{\boldsymbol{\beta}_{\boldsymbol{\sigma(j)}}{}^{\boldsymbol{w_j}}}\right) \tag{1}$$

Here, $\sigma(j)$ denotes the permutation corresponding to the ordered position of the j^{th} PFN.

PF score functions are used to convert each PFN into a single value, allowing criteria to be compared and alternatives to be ranked for decision-making (X. Zhang & Xu, 2014).

To obtain a crisp decision matrix for subsequent MCDM analysis, each aggregated PFN was transformed into a scalar score. Following the score-function approach described by X. Zhang and Xu (2014) and applied by Peng et al. (2020), the score matrix $R = (r_{ij})_{m\times n}$ was calculated using Eq. (2), where $p_{ij} = (\mu_{ij}, \nu_{ij})$ represents the corresponding PFN.

$$r_{ij} = \mu_{ij}^2 - \nu_{ij}^2 - \ln\left(1 + \pi_{ij}^2\right) \tag{2}$$

In Eq. (2), $\pi_{ij} = \sqrt{1 - \mu_{ij}^2 - \nu_{ij}^2}$ represents the indeterminacy degree associated with the corresponding PFN.

The resulting crisp decision matrix was subsequently analysed using integrated MCDM techniques, which provide structured procedures for evaluating multi-criteria decision problems (Avramova et al., 2025).

The CRITIC method was applied to the crisp decision matrix to derive objective weights for the 22 strategic dimensions. CRITIC determines criterion weights by jointly considering the variability of criterion values and their inter-criterion relationships (Diakoulaki et al., 1995). The procedure applied in this study is summarized below (Peng et al., 2020).

Step 1: The crisp score matrix R was normalized using Eq. (3) to obtain the normalized decision matrix $R' = (r'_{ij})_{m\times n}$. For benefit criteria $(j \in B)$ and cost criteria $(j \in C)$, the normalized values were computed as follows.

$$\begin{cases} \boldsymbol{r'_{ij}} = \dfrac{\boldsymbol{r_{ij}} - \boldsymbol{r_j^-}}{\boldsymbol{r_j^+} - \boldsymbol{r_j^-}}, & \boldsymbol{j \in B} \\ \boldsymbol{r'_{ij}} = \dfrac{\boldsymbol{r_j^+} - \boldsymbol{r_{ij}}}{\boldsymbol{r_j^+} - \boldsymbol{r_j^-}}, & \boldsymbol{j \in C} \end{cases} \tag{3}$$

where $\boldsymbol{r_j^-} = \boldsymbol{min_i r_{ij}}$, $\boldsymbol{r_j^+} = \boldsymbol{\max_i r_{ij}}$

For normalization, all 22 strategic dimensions were considered benefit-type criteria, as higher evaluations indicate stronger positive alignment with the sustainability aspects.

Step 2: The mean and standard deviation of the normalized values were calculated for each criterion using Eq. (4). The standard deviation σ_j represents the variability of the criterion values.

$$\boldsymbol{\sigma_j} = \sqrt{\frac{\left(\sum_{\boldsymbol{i=1}}^{\boldsymbol{m}} \left(\boldsymbol{r'_{ij}} - \boldsymbol{\bar{r}_j}\right)^{\boldsymbol{2}}\right)}{\boldsymbol{m}}} \tag{4}$$

where, $\boldsymbol{\bar{r}_J} = \frac{\left(\sum_{i=1}^{m} r'_{ij}\right)}{\boldsymbol{m}}$

Step 3: Pairwise correlation coefficients among the criteria were calculated using Eq. (5). These correlations capture the degree of similarity or conflict in the information represented by different criteria.

$$\boldsymbol{\rho_{jk}} = \frac{\sum_{i=1}^{m} \left(\boldsymbol{r'_{ij}} - \overline{\boldsymbol{r_j}}\right)\left(\boldsymbol{r'_{ik}} - \overline{\boldsymbol{r_k}}\right)}{\sqrt{\sum_{i=1}^{m} \left(\boldsymbol{r'_{ij}} - \overline{\boldsymbol{r_j}}\right)^2}\sqrt{\sum_{i=1}^{m} \left(\boldsymbol{r'_{ik}} - \overline{\boldsymbol{r_k}}\right)^2}} \tag{5}$$

Step 4: The information content c_j of each criterion was determined using Eq. (6), which combines criterion variability with its relationships with the remaining criteria. A larger c_j indicates a greater relative informational contribution within the CRITIC framework.

$$\boldsymbol{c_j} = \boldsymbol{\sigma_j} \sum_{k=1}^{n} \left(\mathbf{1} - \boldsymbol{\rho_{jk}}\right) \tag{6}$$

Step 5: The information-content values were normalized using Eq. (7) to obtain the final objective criterion weights.

$$\boldsymbol{\omega_j} = \frac{\boldsymbol{c_j}}{\sum_{j=1}^{n} \boldsymbol{c_j}} \tag{7}$$

In the final phase, the CoCoSo method was applied to rank the five sustainability aspects. CoCoSo combines additive and multiplicative aggregation mechanisms to derive a compromise evaluation of the alternatives (Yazdani et al., 2019). In the present study, the normalized decision matrix and the objective CRITIC weights were used as inputs to the CoCoSo procedure. The calculation steps, adapted from Peng et al. (2020), are summarized below.

Step 1: The normalized decision matrix R', obtained using Eqs. (1)–(3), was used as the basis for the CoCoSo calculations.

Step 2: The objective criterion weights ω_j, obtained from Eq. (7), were incorporated into the evaluation.

Step 3: For each sustainability aspect, the weighted-sum comparability measure S_i was calculated using Eq. (8).

$$\boldsymbol{S_i} = \sum_{j=1}^{n} \boldsymbol{\omega_j r'_{ij}} \tag{8}$$

Step 4: The corresponding power-weighted comparability measure P_i was calculated using Eq. (9).

$$\boldsymbol{P_i} = \sum_{j=1}^{n} \left(\boldsymbol{r'_{ij}}\right)^{\boldsymbol{\omega_j}} \tag{9}$$

Step 5: Three relative appraisal indices, K_{ia}, K_{ib}, and K_{ic}, were calculated using Eqs. (10)–(12), respectively. These indices represent alternative compromise formulations based on the S_i and P_i measures.

$$\boldsymbol{K_{ia}} = \frac{\boldsymbol{P_i} + \boldsymbol{S_i}}{\sum_{i=1}^{m} (\boldsymbol{P_i} + \boldsymbol{S_i})} \tag{10}$$

$$\boldsymbol{K_{ib}} = \frac{\boldsymbol{S_i}}{\min_i \boldsymbol{S_i}} + \frac{\boldsymbol{P_i}}{\min_i \boldsymbol{P_i}} \tag{11}$$

$$\boldsymbol{K_{ic}} = \frac{\boldsymbol{\lambda S_i} + (\mathbf{1} - \boldsymbol{\lambda})\boldsymbol{P_i}}{\boldsymbol{\lambda} \max_i \boldsymbol{S_i} + (\mathbf{1} - \boldsymbol{\lambda}) \max_i \boldsymbol{P_i}}, \; 0 \leq \lambda \leq 1 \tag{12}$$

Here, K_{ia} represents the arithmetic mean of the sums of Weighted Sum Model (WSM) and Weighted Product Model (WPM) scores, K_{ib} indicates the total of relative scores of WSM and WPM in relation to the optimal score, and K_{ic} provides the balanced compromise of the scores from the WSM and WPM. Eq. (12) uses the value of lambda as λ = 0.5 for analysis.

Step 6: The final CoCoSo assessment value K_i was obtained using Eq. (13) by combining the three appraisal indices.

$$K_i = (K_{ia}K_{ib}K_{ic})^{\frac{1}{3}} + \frac{(K_{ia}+K_{ib}+K_{ic})}{3} \quad (13)$$

Step 7: The sustainability aspects were ranked in descending order of their K_i (i = 1, 2, …, m) values, with a higher value indicating a higher relative composite evaluation within the decision framework.

3. Results

This section presents the results of the PF-based CRITIC–CoCoSo analysis, in which CRITIC determines the objective weights of the strategic dimensions from the information contained in the decision matrix, while CoCoSo uses these weights to rank the five sustainability aspects.

Tables 5–9 present representative excerpts of the experts' linguistic evaluations of the strategic dimensions across the five sustainability aspects. These evaluations form the initial decision matrix and are subsequently converted into corresponding PFNs for further analysis.

Table 5. Linguistic response of Expert 1

	S1	S2	S3	…	…	S20	S21	S22
A1	VH	VH	VH	…	…	M	H	H
A2	L	M	M	…	…	M	M	VH
A3	M	VH	VH	…	…	VH	VL	M
A4	VH	H	H	…	…	H	VH	M
A5	L	H	H	…	…	L	L	M

Table 6. Linguistic response of Expert 2

	S1	S2	S3	…	…	S20	S21	S22
A1	H	VH	VH	…	…	M	H	M
A2	L	L	M	…	…	M	L	H
A3	L	H	H	…	…	VH	M	L
A4	VH	M	H	…	…	H	H	M
A5	L	H	H	…	…	M	VL	L

Table 7. Linguistic response of Expert 3

	S1	S2	S3	…	…	S20	S21	S22
A1	H	H	VH	…	…	M	H	M
A2	VL	M	M	…	…	M	M	VH
A3	M	VH	H	…	…	VH	L	M
A4	VH	M	H	…	…	H	VH	M
A5	L	H	M	…	…	M	L	M

Table 8. Linguistic response of Expert 4

	S1	S2	S3	…	…	S20	S21	S22
A1	H	VH	H	…	…	H	M	L
A2	VL	M	H	…	…	H	L	M
A3	L	VH	VH	…	…	H	VL	VL
A4	H	H	H	…	…	M	VH	L
A5	M	VH	VH	…	…	L	VL	VL

Table 9. Linguistic response of Expert 5

	S1	S2	S3	…	…	S20	S21	S22
A1	M	M	H	…	…	H	M	M
A2	VL	L	M	…	…	M	L	VH
A3	L	H	H	…	…	H	L	L
A4	M	M	M	…	…	M	H	M
A5	VL	M	H	…	…	L	VL	L

Using the PF numbers corresponding to the linguistic terms in Table 4 and the PFOWA operator in Eq. (1), the aggregated matrix that reflects the combined evaluations of the experts was obtained. Table 10 presents an excerpt of the aggregated PF evaluations obtained by combining the individual expert judgements. These evaluations form the group decision matrix and are subsequently converted into crisp scores for MCDM analysis.

Table 10. Aggregated PF decision matrix

	S1	S2	S3	…	…	S20	S21	S22
A1	(0.74, 0.33)	(0.83, 0.19)	(0.85, 0.17)	…	…	(0.60, 0.51)	(0.64, 0.47)	(0.53, 0.59)
A2	(0.21, 0.86)	(0.44, 0.67)	(0.55, 0.55)	…	…	(0.55, 0.55)	(0.40, 0.71)	(0.83, 0.19)
A3	(0.40, 0.71)	(0.85, 0.17)	(0.81, 0.23)	…	…	(0.85, 0.17)	(0.31, 0.79)	(0.38, 0.73)
A4	(0.83, 0.19)	(0.60, 0.51)	(0.67, 0.43)	…	…	(0.64, 0.47)	(0.85, 0.17)	(0.47, 0.64)
A5	(0.33, 0.77)	(0.74, 0.33)	(0.74, 0.33)	…	…	(0.40, 0.71)	(0.21, 0.86)	(0.38, 0.73)

The score function in Eq. (2) was used to obtain a defuzzified score matrix with crisp values. Table 11 presents an excerpt of the defuzzified score matrix derived from the aggregated PF evaluations. The resulting crisp values allow comparison across strategic dimensions and sustainability aspects and provide the input for subsequent weighting and ranking analyses.

Table 11. Defuzzified decision matrix with crisp values

	S1	S2	S3	…	…	S20	S21	S22
A1	0.144028	0.421499	0.463159	…	…	-0.226957	-0.133926	-0.385966
A2	-0.893224	-0.568864	-0.328453	…	…	-0.328453	-0.638755	0.421499
A3	-0.638755	0.463159	0.348356	…	…	0.463159	-0.778123	-0.669909
A4	0.421499	-0.226957	-0.048552	…	…	-0.133926	0.463159	-0.502418
A5	-0.744813	0.144028	0.144028	…	…	-0.638755	-0.893224	-0.669909

A normalized score matrix was obtained using Eq. (3). Table 12 presents the normalized values used in the CRITIC analysis. Normalization ensures comparability across criteria and provides the basis for assessing criterion variability and inter-criterion relationships.

Table 12. Normalized score decision matrix

	S1	S2	S3	…	…	S20	S21	S22
A1	0.788951	0.959633	1.000000	…	…	0.373712	0.559796	0.260162
A2	0.000000	0.000000	0.000000	…	…	0.281603	0.187609	1.000000
A3	0.193553	1.000000	0.854976	…	…	1.000000	0.084859	0.000000
A4	1.000000	0.331298	0.353584	…	…	0.458138	1.000000	0.153463
A5	0.112884	0.690771	0.596859	…	…	0.000000	0.000000	0.000000

Using Eqs. (4)–(7), the standard deviation, information content, and objective weights corresponding to each criterion were obtained. Table 13 presents the criteria in descending order of their CRITIC weights to clearly indicate their relative informational contribution within the decision matrix. S7 (easily accessible e-waste collection centres) received the highest CRITIC weight (0.071678), followed by S14 (circular value marketing, 0.057246), S10 (economic reward systems, 0.056847), S18 (development of value-added products, 0.051553), and S5 (public awareness, 0.050899), indicating

their relatively greater contribution to the information captured by the decision matrix. It is important to note that CRITIC weights are determined by criterion variability and inter-criterion conflict; therefore, a lower weight does not imply that a strategic dimension is unimportant for CE implementation.

Table 13. Standard deviation, information content, objective weights, and ranking of the criteria in descending order of weight

Criterion	SD	Information Content	Weight	CRITIC Weight Rank
S7	0.485175	13.296800	0.071678	1
S14	0.397049	10.619539	0.057246	2
S10	0.434421	10.545591	0.056847	3
S18	0.387449	9.563486	0.051553	4
S5	0.383122	9.442248	0.050899	5
S22	0.415803	9.271757	0.049980	6
S11	0.427379	8.677602	0.046777	7
S2	0.427115	8.667470	0.046723	8
S6	0.486032	8.547971	0.046079	9
S17	0.397159	8.256813	0.044509	10
S16	0.388900	8.013766	0.043199	11
S19	0.476250	7.913910	0.042661	12
S3	0.399428	7.804206	0.042069	13
S1	0.445679	7.798284	0.042037	14
S9	0.401720	7.756921	0.041814	15
S13	0.443616	7.577990	0.040850	16
S21	0.413622	7.416808	0.039981	17
S8	0.372409	7.320902	0.039464	18
S12	0.405886	7.176688	0.038687	19
S20	0.365894	7.019645	0.037840	20
S4	0.356754	6.794519	0.036626	21
S15	0.362903	6.025509	0.032481	22

CoCoSo results were obtained using Eqs. (8)–(13). Table 14 presents the final CoCoSo scores and ranking of the five sustainability aspects. Environmental sustainability ranked first with the highest composite score (2.606647), followed by governance (2.306283), economic (2.254314), social (2.050147), and cultural sustainability (1.349340). These results highlight the relative prominence of environmental sustainability within the evaluated CE framework, while the other aspects represent complementary dimensions of the broader sustainability transition.

Table 14. CoCoSo results corresponding to each alternative

Alternative	S	P	K_{ia}	K_{ib}	K_{ic}	CoCoSo score	Rank
A1	0.565679	20.428243	0.24618	3.672823	1	2.606647	1
A4	0.47968	18.34458	0.220738	3.219804	0.896653	2.306283	2
A3	0.447911	18.204421	0.218722	3.117355	0.888463	2.254314	3

A2	0.42532	16.321365	0.196376	2.860661	0.797692	2.050147	4
A5	0.361005	9.700642	0.117985	2.000000	0.479265	1.349340	5

3.1. Sensitivity analysis

To test the stability of the results, a total of 110 scenarios were created for the sensitivity analysis by increasing each criterion weight by 10–50% and adjusting the other weights accordingly. The results revealed that the relative rankings of all alternatives remained consistent across all 110 scenarios , yielding a stability percentage of 100%. The consistent ranking of alternatives across all scenarios suggests that the ranking results are highly robust and not significantly influenced by changes in the weighting structure. To further test the robustness of the results, the same decision problem was evaluated using an alternative MCDM framework: MEREC–MARCOS (Keshavarz-Ghorabaee et al., 2021; Mahmoudian Azar Sharabiani & Mousavi, 2023). MEREC (MEthod based on the Removal Effects of Criteria) generated a new set of objective criterion weights, while MARCOS (Measurement Alternatives and Ranking according to COmpromise Solution) ranked the five sustainability aspects. Despite the change in methodology, the ranking remained unchanged: Environmental, Governance, Economic, Social, and Cultural sustainability, in descending order. The two frameworks showed perfect rank agreement (Spearman's $\rho = 1.000$). The consistent rankings obtained from two different objective weighting and MCDM frameworks, together with the criterion-weight sensitivity analysis, further support the robustness and stability of the findings. Table 15 compares the rankings of the five sustainability aspects obtained using the original PF-based CRITIC–CoCoSo framework and the alternative PF-based MEREC–MARCOS framework.

Table 15. Comparison of sustainability aspect rankings obtained using PF-based CRITIC–CoCoSo and PF-based MEREC–MARCOS frameworks

Sustainability aspect	CRITIC–CoCoSo rank	MEREC–MARCOS rank
Environmental	1	1
Governance	2	2
Economic	3	3
Social	4	4
Cultural	5	5

Note: Spearman's rank correlation coefficient (ρ) = 1.000.

4. Discussion

The CRITIC analysis assigns objective weights to the 22 CE strategic dimensions based on their variability and relationships with other criteria in the decision matrix. The weights of the 22 strategic dimensions range from 0.032481 to 0.071678, indicating variation in the discriminatory information contributed by the criteria. Since CRITIC weights are derived from criterion variability and inter-criterion relationships, they should not be interpreted as direct measures of perceived importance. Instead, they indicate the relative informational contribution of each criterion to the subsequent MCDM evaluation. The relatively small variation in CRITIC weights suggests that no single criterion dominates the decision matrix. Instead, several dimensions—particularly those related to collection infrastructure, market mechanisms, consumer participation, value-added product development, and occupational safety—make comparatively stronger informational contributions. This indicates that CE implementation is shaped by multiple interrelated strategic dimensions rather than a single dominant factor. Viewed alongside the supporting literature, the results also highlight the interconnected roles of infrastructure, markets, behavioural engagement, and worker protection. However, the CRITIC weights reflect informational contribution and should not be interpreted as direct measures of substantive importance or as a basis for resource allocation. The findings therefore position the CE transition in India's electronics sector as a systemic challenge rather than merely a technological or recycling issue, requiring coordinated action across multiple actors and stages of the value chain.

Easily accessible e-waste collection centres (0.071678) obtained the highest CRITIC weight, indicating the greatest relative informational contribution among the evaluated criteria. Collection centres mark the beginning of the reverse logistics chain. How well they operate affects recycling rates and the

recovery of important raw materials, thereby reducing waste leakage into the environment (Arya & Kumar, 2020; Fiksel et al., 2021).

Circular value marketing (0.057246), economic reward systems (0.056847), and the development of value-added products (0.051553) were also among the relatively higher-weighted criteria, indicating comparatively greater informational contribution within the CRITIC analysis. Previous studies further support their practical relevance by highlighting the role of market incentives in strengthening consumer participation and encouraging reuse and recycling practices (Bressanelli et al., 2021; Jaiswal & Mukti, 2025). Public awareness received a comparatively high CRITIC weight (0.050899), consistent with earlier research showing that education can influence recycling behaviour and strengthen participation in formal recycling systems (Jaiswal et al., 2023). The findings broadly align with earlier studies that emphasize effective collection, consumer participation, regulatory support, and resource recovery as key to advancing CE in the electronics sector. This study extends these insights by examining such interventions together within a multidimensional sustainability framework rather than as separate issues. The findings further highlight the interdependence of collection systems, consumer participation, and economic value creation. The prominence of accessible e-waste collection centres reinforces concerns over collection and channelization in India, while the importance of circular value marketing, economic incentives, and public awareness highlights the role of consumer- and market-oriented measures. Expanding collection infrastructure alone may not ensure effective e-waste channelization unless consumers are aware of formal disposal options and motivated to use them. Economic incentives can encourage return behaviour, while circular value marketing can strengthen awareness of the environmental and economic benefits of responsible disposal. At the same time, creating value-added products from recovered materials can improve the commercial viability of resource recovery. These dimensions should therefore be pursued as complementary measures rather than treated as independent priorities.

The research-driven occupational safety framework for workers also received a relatively high CRITIC weight (0.049980), reflecting its stronger informational contribution within the decision matrix. This practical relevance is supported by earlier studies that identify exposure to toxic materials as a major concern, particularly for workers engaged in informal and manual e-waste handling (Murthy & Ramakrishna, 2022). Servitized/product-service models (0.046777), along with resource-efficient 10R strategies (0.046723), help move the system from a linear disposal approach to a more circular and resource-efficient one (Pan et al., 2022). Collaborative integration of formal and informal e-waste sectors (0.046079) and knowledge-driven workforce advancement (0.044509) received moderate CRITIC weights. Their substantive relevance is nonetheless supported by previous research emphasizing the need to integrate informal actors and strengthen workforce capabilities for safe and effective recovery processes (Murthy & Ramakrishna, 2022).

In product-service models, manufacturers continue to be involved with their products throughout their life cycle, including after customer use. Since companies continue to be responsible for their products, they are more likely to repair, refurbish, remanufacture, and reuse them rather than dispose of them. This helps put the 10R strategy into practice. For these practices to work well, used products need to be collected properly. Therefore, collaboration between the formal and informal e-waste sectors is essential. In addition, the efficient management of such circular systems requires a skilled and knowledgeable workforce capable of carrying out recovery operations and other CE activities.

Incorporating Extended Consumer Responsibility (ECR) in regulations (0.043199), adaptive legislation and evidence-based recycling policies (0.042037), and strengthening EPR compliance (0.041814) received moderate CRITIC weights, indicating moderate informational contributions within the decision matrix. Their substantive relevance to CE implementation is nevertheless well established in the literature, particularly through their role in regulatory compliance, producer accountability, and formal processing. Studies show that EPR regulations have improved formal processing capacity in India; however, only 5–15% of e-waste is channelled to formal facilities because of limited consumer-friendly collection mechanisms and the continuing dominance of informal collectors (Bhaskar & Turaga, 2018). This evidence reinforces the practical relevance of collection systems and formal–informal sector coordination without implying that their CRITIC weights constitute direct measures of substantive priority. Adequate legislation also ensures cross-border monitoring for e-waste movement

(0.039981) as laws help in managing the import, export, and transboundary movement of e-waste while ensuring that international rules and environmental standards are followed.

Digitally monitored resource recovery systems (0.042661), sustainable product design (0.042069), and technology-driven innovations (0.040850) received moderate CRITIC weights, reflecting moderate informational contributions within the decision matrix. Their practical relevance is supported by previous research linking these approaches to greater recycling transparency, improved material traceability, better product design, and more efficient resource recovery (Pan et al., 2022). Technologies such as automated sorting and AI-assisted material recovery can make recycling processes more efficient (Golpeo et al., 2025). Technologies such as the Internet of Things (IoT), big data, and artificial intelligence (AI) can help improve product design by providing detailed information about materials. This makes it easier to avoid harmful materials and develop products that are more durable, repairable, and recyclable (Ghoreishi & Happonen, 2020).

Integrated stakeholder cooperation (0.038687) is viewed as an effective way to expand responsible recycling practices (0.039464) (Cao et al., 2024) while protecting the livelihoods of people involved in the sector, especially in developing countries such as India. Revenue-generating financial strategies (0.037840), structured reverse logistics infrastructure (0.036626), and LCA (0.032481) draw attention to the fact that environmental protection efforts still need to be economically viable to succeed in the long run (Jain et al., 2022). Although these dimensions received comparatively lower CRITIC weights, these lower weights indicate relatively lower informational contribution within the present decision matrix and should not be interpreted as evidence of lower substantive importance for CE implementation.

The CRITIC analysis assigns comparatively higher informational weights to several front-end dimensions, including accessibility, incentive mechanisms, and marketing-related measures. Their substantive relevance is also supported independently in the CE literature (Torkayesh et al., 2022).

Recent evidence further supports these findings. NITI Aayog (2026) emphasizes stronger collection and recycling infrastructure, formalization of the e-waste ecosystem, and more effective EPR mechanisms to advance circularity in India. Recent studies similarly identify persistent challenges in e-waste channelization, informal-sector integration, technological readiness, and regulatory implementation, underscoring the need to complement infrastructure development with coordinated governance and technological interventions (Prakash et al., 2026; Bhardwaj & Chatterjee, 2026).

The ranking of sustainability aspects according to CoCoSo score—environmental (2.606647), governance (2.306283), economic (2.254314), social (2.050147), and cultural (1.349340)—shows that environmental protection receives the greatest relative composite evaluation across the weighted CE strategic dimensions considered in the study. The ranking reflects the relative performance of the sustainability aspects within the specified decision framework rather than evidence that environmental sustainability constitutes the primary objective or motivation for CE adoption. The emphasis on environmental factors highlights the importance of addressing pollution, limiting landfill use, and improving the recovery of valuable resources from electronic waste (Quinto et al., 2025).

Governance ranks second in the CoCoSo analysis, indicating a relatively strong overall evaluation under the weighted CE strategic dimensions. The high ranking of the governance aspect highlights the important role of effective regulations and EPR/ECR policies in improving collection, ensuring compliance, and supporting CE goals. Although EPR/ECR frameworks have strengthened the regulatory landscape, studies continue to highlight issues related to policy coordination, enforcement gaps, and their limited effectiveness in promoting eco-design and producer accountability (Compagnoni, 2022). This indicates that regulations alone are not enough. They must be designed according to local needs and circumstances to be effective.

The economic aspect occupies the third position, indicating a moderate relative position within the five sustainability aspects evaluated in the present decision framework. This suggests that economic considerations play an important role, although they are often seen as supporting environmental and governance goals rather than being the primary objective of CE adoption in India's electronics domain (Jain et al., 2022).

Social sustainability occupies the fourth position in the CoCoSo ranking, indicating a comparatively lower composite evaluation across the weighted CE strategic dimensions considered in the present decision framework. This may be because, despite its significance, issues such as the inclusion of informal workers and the provision of safe working conditions remain unresolved challenges in the CE transition (Xavier et al., 2023).

Cultural sustainability ranks fifth in the CoCoSo analysis, reflecting a relatively lower overall evaluation under the weighted CE strategic dimensions. Cultural sustainability reflects the values, social norms, knowledge, and behaviours that shape how individuals and communities engage with sustainability transitions. In a CE context, these factors influence the adoption and continuity of sustainable practices related to consumption, disposal, reuse, and resource use (Srivastav et al., 2023).

The comparatively lower CoCoSo scores of the social and cultural aspects reflect lower composite evaluations within the present framework rather than lower inherent importance for CE implementation.

Taken together, the sustainability rankings reveal a layered pattern of CE priorities. The top ranking of environmental sustainability aligns with the strong environmental focus of CE and e-waste research, particularly on pollution prevention, resource recovery, landfill reduction, and responsible recycling. Governance ranking second underscores the institutional foundations of CE and supports earlier emphasis on EPR, regulatory enforcement, and stakeholder coordination. Economic sustainability ranked third, suggesting that economic viability remains important for sustaining circular practices, although it was less prominent than environmental and governance considerations within the present framework. The lower rankings of social and cultural sustainability do not imply that these dimensions are less important; rather, they were less prominent under the strategic dimensions and expert judgements considered in this study. This finding points to the need for greater attention to occupational safety, informal-sector integration, consumer responsibility, behavioural change, and workforce development, all of which are important for an inclusive and sustained circular transition.

The robustness analyses further support the stability of the results. Environmental sustainability remained the top-ranked aspect across all 110 criterion-weight variation scenarios, while MEREC–MARCOS reproduced the same ordering as CRITIC–CoCoSo (Spearman's $\rho = 1.000$). The agreement across both weight variations and an alternative MCDM framework suggests that the ranking remains stable under the conditions examined. However, the result should not be interpreted as diminishing the relevance of the other dimensions; rather, it demonstrates that environmental considerations remain the most consistently prioritized across different weighting configurations.

4.1. Practical applicability and stakeholder implications

The practical value of the proposed framework lies in providing structured decision support for understanding the relative informational contribution of CE strategic dimensions and the comparative positioning of sustainability aspects. The CRITIC weights should not be interpreted as direct measures of substantive importance or as automatic prescriptions for resource allocation. Rather, they can be considered alongside contextual evidence, stakeholder needs, regulatory requirements, implementation feasibility, and relevant literature when formulating CE interventions. Accordingly, dimensions such as accessible e-waste collection centres, circular value marketing, economic incentives, public awareness, occupational safety, formal–informal sector integration, EPR compliance, and workforce development remain practically relevant based on the broader CE context and supporting literature examined in this study. The framework can therefore inform, rather than determine, stakeholder prioritization and resource-allocation decisions.

The identified strategic dimensions and analytical findings have different implications for stakeholders across the electronics ecosystem. Table 16 links these priorities to stakeholder-specific actions, demonstrating how the framework can assist practical decision-making.

Table 16. Stakeholder-specific implications of the study

Stakeholder	Key findings relevant to the stakeholder	Practical implications
Government and regulatory bodies	Collection access, EPR/ECR, legislation, digital monitoring and cross-border monitoring	Strengthen accessible collection networks, EPR/ECR compliance and monitoring mechanisms; develop context-specific policies and improve traceability of e-waste flows.
Electronics manufacturers/OEMs	Circular value marketing, product-service models, 10R strategies and sustainable product design	Integrate circularity into product design and business models; strengthen take-back, repair, refurbishment, remanufacturing and circular value communication.
Recyclers and waste-management firms	Collection access, responsible recycling, technology-driven innovation and occupational safety	Improve collection and recovery systems, adopt safer recycling practices and advanced recovery technologies, and strengthen worker protection.
Informal-sector actors/organizations	Formal–informal integration, occupational safety and workforce advancement	Promote role-based integration with formal systems, skill development, safer working practices and participation in organized collection and recovery networks.
Consumers	Public awareness, economic rewards and consumer responsibility	Encourage responsible return and disposal through awareness initiatives, convenient collection options and appropriate economic incentives.
Industry associations and supporting institutions	Stakeholder cooperation, workforce development and research-driven interventions	Facilitate collaboration among manufacturers, recyclers, government, researchers and other actors; support training, knowledge sharing and CE-oriented initiatives.
Researchers and academia	Integrated PF-based CRITIC–CoCoSo framework and multidimensional sustainability assessment	Apply and extend the framework to other industries, geographical settings and stakeholder groups, and evaluate CE strategies using alternative decision-making approaches.

5. Conclusion

The study employed an integrated MCDM framework to evaluate the 22 CE strategic dimensions with respect to the five key sustainability aspects in the context of India's electronics sector. CRITIC was used to derive objective weights for the strategic dimensions based on their variability and inter-criterion relationships, while CoCoSo ranked the five sustainability aspects using these weighted dimensions. This approach enabled the simultaneous evaluation of environmental, social, economic, governance, and cultural aspects of sustainable development, resulting in a systematic and balanced decision-making structure. Among the five aspects, environmental sustainability was the highest-ranked, while governance, economic, social, and cultural aspects followed in that order. The weights of strategic dimensions exhibit moderate variation, indicating that the informational contribution within the decision matrix is distributed across multiple strategic dimensions rather than being concentrated in a single criterion. Accessible collection centres, market incentives, and awareness mechanisms are among the dimensions exhibiting relatively higher objective weights. The framework provides insights to key stakeholders for developing policies and strategies that support all dimensions of sustainability and accelerate the transition towards a circular electronics sector in India.

6. Limitations and future research directions

Despite its contributions, the study has certain limitations that offer directions for future research. Although the expert panel included experienced industry and academic professionals, it did not directly represent policymakers, NGOs, informal-sector actors, or consumer groups which may have limited the diversity of stakeholder perspectives represented in the evaluation. As a result, some perspectives relevant to the social, cultural, and governance dimensions of CE may not be fully reflected in the findings. Future studies could therefore involve a larger and more heterogeneous panel comprising policymakers, manufacturers, recyclers, informal-sector representatives, and other relevant actors to

assess whether the identified priorities remain consistent across different groups. The analysis also relies on expert judgements and may be influenced by individual perceptions, although the PF framework helps account for uncertainty and vagueness in linguistic assessments. Moreover, as the study focuses specifically on the Indian electronics industry, the relative CRITIC weights and informational contributions of the identified strategic dimensions may differ across sectors and geographical contexts, providing scope for sectoral and cross-country comparisons. Future research could also employ alternative fuzzy frameworks, such as spherical or hesitant fuzzy sets, together with MCDM methods such asFUCOM (Full Consistency Method)and MULTIMOORA (Multi-Objective Optimization on the basis of a Ratio Analysis plus the full MULTIplicative form), to assess the robustness and methodological consistency of the findings.

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Data availability

The data supporting the findings of this study are available in https://doi.org/10.5281/zenodo.20671109. The dataset includes primary data collected and analysed during the current study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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