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A stakeholder-centric fuzzy AHP-TOPSIS framework for prioritizing challenges and solutions in the sustainable circular supply chain of electric vehicle batteries

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ABSTRACT

The worldwide shift to electric mobility has rendered the establishment of sustainable and circular electric vehicle (EV) battery supply chains an immediate imperative. This study proposes a stakeholder-centric, hybrid multi-criteria decision-making framework that incorporates Fuzzy Analytical Hierarchy Process and Fuzzy Technique of Order of Preference by Similarity to Ideal Solution to prioritize challenges and solutions in the EV battery supply chain. Drawing on stakeholder and sustainability theories, the framework evaluates 10 primary challenge domains, 35 sub-challenges, and 14 solution strategies based on insights from six key stakeholder groups: mining and resource extraction, raw material procurement, manufacturing and product development, supply chain and logistics, product management and strategy, and research and development. FAHP results identify environmental resource and lifecycle concerns and supply network robustness and economic stability as the most significant challenge areas. At the sub-criteria level, stakeholders prioritized scarcity and sustainability of vital resources and vulnerabilities in supply chain architecture. FTOPSIS analysis ranks policy framework and compliance and collaborative and stakeholder engagement as the most influential and widely endorsed solution strategies. A foresight-based sensitivity analysis for the year 2040 compares two contrasting future scenarios: a fully developed circular battery ecosystem and another marked by global supply chain volatility and heavy import dependence. Innovation-driven solutions dominate the former, while policy preparedness and economic incentives dominate in the latter. This study offers a novel, transferable framework that aligns stakeholder priorities with circular economy objectives, providing strategic guidance for fostering resilient and sustainable EV battery supply chains across global regions.

1. Introduction

The vehicle industry is accountable for a large share of the greenhouse gas released into the earth's atmosphere (UN Environment Programme, 2021). Specifically, it contributes to more than 30 % of the total worldwide emission of GHG, which is the main driver of climate

Abbreviations: EV, Electric vehicles; SC, Supply chain; R&D, Research and development; EOL, End-of-life; RBV, "Resource-based view; CSC, Circular supply chain; ST, Stakeholder theory; CE, Circular economy; MCDM, "Multi-criteria decision-making"; EPR, Extended producer responsibility; FAHP, "Fuzzy analytical hierarchy process"; FTOPSIS, "Fuzzy technique for order preference by similarity to ideal solution"; RI, Random consistency index; DMs, Decision makers; CR, "Consistency ratio"; FPIS, "Fuzzy Positive Ideal Solution"; FNIS, "Fuzzy Negative Ideal Solution"; TFN, Triangular fuzzy number; ERL, Environmental resource and lifecycle concerns; CRM, Circular recovery systems and material reuse; SMS, Sustainable materials and resource substitution; SNR, Supply network robustness and economic stability; OSP, Operational sustainability and process integrity; EESG, Environmental, social, economic, and governance; HER, Human-centered and ethical risk dimensions; TSI, Technological scalability and infrastructure gaps; GRA, Governance, standards, and regulatory alignment; DIT, Digital integration for supply chain transparency; RGD, Research-driven gaps and knowledge deficiencies; ST, Stakeholder Theory.

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change (UN Environment Programme, 2021). This significant contribution underscores the urgency of transitioning to sustainable solutions in alignment with the Paris Climate Agreement's goals to mitigate air pollution and climate change (Dagnachew et al., 2021). Among these solutions, electric vehicles (EVs) have emerged as a crucial breakthrough, minimizing lifecycle emissions by up to 70 % compared to internal combustion engine vehicles (McKerracher, 2024). The worldwide EV market is extensively increasing, with projections of market penetration growing from 17.5 million units in 2024 to much higher levels by 2030 (Tomić, 2024). However, despite their potential to decarbonize the transportation sector, EVs also present considerable challenges, particularly concerning the manufacturing, utilization, and disposal of batteries (Udendhran et al., 2025).

EV battery manufacturing is highly resource-intensive, leading to substantial carbon emissions, while improper disposal can cause toxic environmental hazards (Jaramillo, 2024; Helfrich, 2023). According to (Fortune Business Insights, 2024; Energy Agency, 2024), the global EV battery demand was etimated at USD 59.06 billion and is projected to reach USD 111.20 billion in 2030. This reflects rapid industrial expansion but also intensifies sustainability risks across production and end-of-life (EOL) stages (Melin et al., 2021). EV batteries, especially lithium-ion, depend on critical components like lithium, nickel, and cobalt (Kalungi et al., 2024). These materials are obtained through environmentally intensive and socially controversial processes, mainly concentrated in a limited, geopolitically sensitive area (Llamas-Orozco et al., 2023). Midstream battery production is highly energy-intensive, often reliant on fossil-based power systems. At the downstream stage, insufficient collection, repurposing, and recycling processes contribute to material loss, fire risks, and hazardous waste (Lal and You, 2023). Concerningly, battery production alone can represent 30–40 % of an EV's total lifecycle emissions (BloombergNEF, 2023). As the industry expands, the prevailing linear "extract–use–discard" supply chain (SC) is becoming increasingly unsustainable, presenting both environmental and economic risks (Greer and Loorbach, 2022).

To alleviate these risks, circular economy (CE) theory posits systematic transformation from traditional production models to circular supply chain (CSC) models that promote closed-loop practices throughout the battery lifecycle (Afroozi et al., 2025). These models emphasize strategies including reuse, repurposing, remanufacturing, and recycling to extend battery functionality and retain essential materials within the system (Afroozi et al., 2025). But implementing the large scale of CSC remains a significant problem (Afroozi et al., 2025). Challenges comprise inefficient reverse logistics, inadequate economic incentives for recycling, weak design-for-disassembly measures, inadequate traceability mechanisms, and disagreement of international laws (Chen et al., 2024). Fig. 1 illustrates the structure of a circular EV battery SC and highlights primary sustainability challenges inherent at each stage. Fig. 1 demonstrates that the electric car battery SC has three primary phases: upstream, midstream, and downstream, each associated with distinct stakeholder groups and offering sustainability problems. The diagram delineates six essential players within this framework: mining and resource extraction, raw material acquisition, manufacturing and product innovation, SC and logistics, product management and strategy, and research and development (R&D). It delineates material flows, feedback loops, and a circular loop is vital for facilitating closed-loop processes. Fig. 1 vividly associates stakeholder responsibilities with systemic difficulties, underscoring the necessity for integrated circular strategies, cross-sector collaboration, and adaptive decision-making throughout the battery lifecycle.

These challenges are further intensified by global SC vulnerabilities (Afroozi et al., 2025). Numerous economies lack cohesive systems for EOL battery recovery, struggle with informal or recycling markets, and encounter limited institutional capacity for cross-sector coordination (Farooki et al., 2023). Data silos, fragmented regulatory enforcement, and unstable critical elements markets diminish SC transparency and resilience (Ishola Bayo Ridwan, 2025). These constraints are particularly

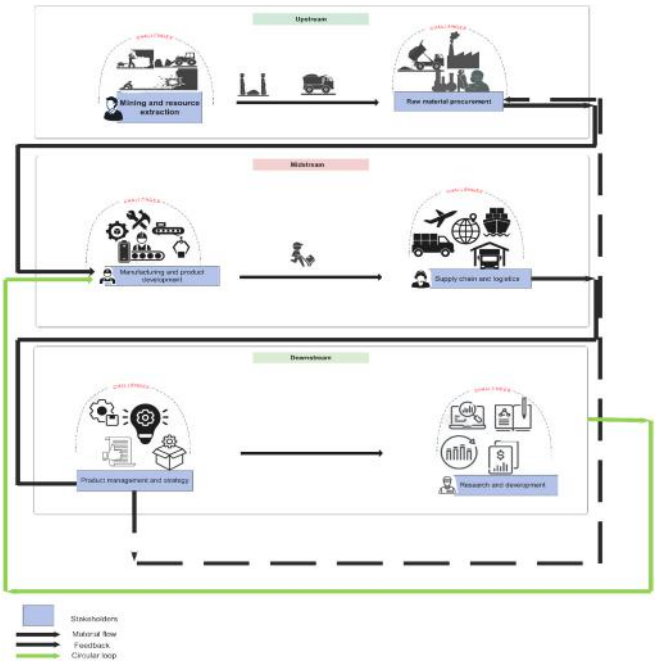

Fig. 1. Stakeholder landscape and sustainability challenges across the circular EV battery supply chain.

stringent in developing and emerging economies, where rapid EV adoption frequently surpasses the necessary infrastructure, governance, and technical capacity for sustainable battery management (Afroozi et al., 2025).

Although scholarly attention to EV battery SCs is increasing, the existing research often lacks to capture the multi-dimensional nature of sustainability in this domain. Many studies take a descriptive method, focusing narrowly on environmental aspects that overlook economic and social trade-offs. Studies like Giri et al. (2024) presented a Delphi-graph theory approach (GTMA) hybrid technique to emphasize challenges in the EV battery sector. However, the Fuzzy Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS) framework advances this approach by integrating fuzzy logic to mitigate expert uncertainty, categorizing insights by stakeholder groups for contextual significance, and facilitating performance-based solution ranking for more pragmatic and adaptive decision-making. Gebhardt et al. (2022) offered a Delphi based mixed methods model for identifying and prioritizing sustainability aspects In EV battery SC. However, their approach lacks in expressing vagueness in data and stakeholder divergence, where the integration of FAHP-FTOPSIS model is helpful in mitigating this issue by using the fuzzy logic, structured decision-making and stakeholder-centric segmentation for enhancing precision and applicability.

Dhairiyasamy et al. (2024) emphasized challenges without including organized ranking framework. Hence constraining their practical applicability. Besides, only less studies ensure systematic stakeholder-oriented prioritization techniques, considering conflicts and decision-making uncertainty. Still no exiting study has applied the integrated FAHP-FTOPSIS technique particularly to the EV battery field. For instance, Salehi Heidari et al. (2018) and Gupta et al. (2025) employed this integration on automative industry and Li (2024) applied FAHP exclusively to assess SC disruption risks in EV industry but the study didn't incorporate FTOPSIS. As a result, this leaves policymakers, producers as well as recyclers with the limited tools to navigate complex decision regarding SC circularity, material recovery along with long-term resilience in EV battery sector.

This study draws on stakeholder theory (ST) (Freeman, 2010) which underscores the importance of involving diverse stakeholder with

different levels of authority, legitimacy, and intensity in the decision-making process (Mitchell et al., 1997). This perspective explains the unique interest of primary SC players included in the sustainability of EV batteries (Chirumalla et al., 2022). This study implements a cohesive theoretical model that merges multiple complementary opinions. ST establishes the foundation for incorporating the distinct and sometimes conflicting the viewpoints, goals as well as the needs of all stakeholders included in the battery value chain. (Chirumalla et al., 2022). The stakeholders are mining and resource extraction entities concerned with environmental degradation and social responsibility at the source (Mutti et al., 2012); raw material procurement players prioritizing geopolitical stability, pricing, and sourcing risks (Lapko et al., 2016); manufacturing and product developers focuses on cost-efficiency, scale, and material performance (Leachman et al., 2005); product management and strategy teams tasked with facilitating circularity through EOL conscious design choices (Burke et al., 2023); R&D stakeholders assigned to advancing innovations in materials, battery life extension as well as recycling technologies (Wrålsen et al., 2021). By incorporating several perspectives through ST, this work ensures that the identification, classification, and prioritization of challenges including both theoretical principles and practical complexities. The stakeholder-specific segmentation used in the FAHP-FTOPSIS approach is directly based on this theoretical framework.

Sustainability theory which focuses on triple bottom line (environmental, social and economic) aspects is used as the primary model for classifying challenges and evaluating the balancing competing goals (Azmat et al., 2023). Together these theories help in recognizing, organizing, and ranking of sustainability issues within EV battery SCs. This approach is grounded in theoretically strong and applicable in real world scenarios.

This work performed a hybrid fuzzy multi-criteria decision-making (MCDM) strategy, incorporating the FAHP and the FTOPSIS. This combination facilitates effective prioritizing of challenges and solutions, even when expert opinions are uncertain or expressed using ambiguity languages. The methodology is used in the context of a developing economy, offering insights relevance to other regions facing similar SC, environmental, and policy related issues.

This research aims to explore the following key research questions (RQs):

RQ 1: What are the main challenges delaying the sustainability of EV battery SCs in emerging markets?
RQ 2: How do stakeholder perspectives differ in prioritizing these challenges and corresponding solutions?
RQ 3: How can fuzzy MCDM techniques be leveraged to systematically evaluate and rank these priorities?
RQ 4: What strategies can enhance circularity, resilience, and long-term viability of EV battery SCs?

In alignment with these questions, the study pursues four main objectives. First, it aims to identify and categorize key sustainability challenges spanning environmental, economic, and social dimensions through expert input and literature synthesis. Second, it evaluates the relative significance of these challenges from a stakeholder-specific lens to capture the diversity of priorities across the SC. Third, it applies the hybrid FAHP–FTOPSIS method to rank both challenges and solution strategies under conditions of uncertainty. Fourth, it develops a practical and scalable decision-support tool to inform sustainability-oriented policy, investment, and operational planning within EV battery ecosystems. Collectively, these objectives ensure the study not only address existing theoretical and methodological gaps but also deliver real-world applicability.

To achieve these objectives, the study adopts a structured and multi-step approach. It begins with a comprehensive review of literature and expert consultations to identify sustainability challenges across the EV battery lifecycle. These are organized using ST and sustainability theory ensuring both conceptual rigor and practical relevance. FAHP is then applied to capture stakeholder-specific priorities under uncertainty, followed by FTOPSIS to systematically rank both challenges and solution strategies. Finally, foresight-based scenario analysis for 2040 is incorporated to test the robustness of results under contrasting future contexts.

The major contribution of this research lies in offering a stakeholder-oriented and uncertainty-resilient decision-support tool for sustainable EV battery SCs. Theoretically, it integrates stakeholder and sustainability theories to provide a holistic framework where methodologically, it advances fuzzy MCDM by combining FAHP–FTOPSIS with long-term foresight and practically, it delivers actionable insights tailored to emerging economies, where fragmented SCs and regulatory gaps make circular transitions particularly challenging.

The subsequent sections of the paper are organized as follows: Section 2 examines the literature on sustainable EV battery SCs; Section 3 delineates the research methodology; Section 4 articulates the results alongside the empirical findings; Section 5 provides research limitations and future directions; and Section 6 concludes with essential insights and prospective research avenues.

1.1. Novelty

This study introduces several innovations that collectively advance the state of research on circular and sustainable EV battery supply chains. Unlike generic frameworks, the approach developed here is distinctive in four ways.

- First, it pioneers stakeholder-specific prioritization, where six key groups are analyzed independently rather than aggregated. This enables the identification of diverse and sometimes conflicting priorities, producing insights that are more context-sensitive and operationally relevant.
- Second, the framework employs an integrated sustainability lens, mapping each challenge and solution across environmental, economic, social, and governance dimensions. This structured alignment ensures that trade-offs are explicitly captured rather than treated in isolation.
- Third, it incorporates foresight-based scenario analysis that extends the evaluation horizon to 2040. By testing priorities against divergent future conditions, the framework offers decision-makers a way to stress-test resilience and adaptability over time an element rarely embedded in MCDM approaches.
- Finally, the framework is explicitly tailored to the realities of emerging economies where fragmented SCs, informal-sector participation, and evolving policy regimes demand approaches that are both rigorous and adaptable.

In addition, this study advances beyond prior works by linking methodological innovation to practical application. The dual-layer prioritization of challenges and solutions provides policymakers with evidence to design phased recycling mandates, extended producer responsibility (EPR) targets, and CE regulations that are sensitive to diverse stakeholder priorities. For industry actors, the framework supports resource allocation decisions, guiding investments in recycling infrastructure, reverse logistics, and second-life applications. By embedding foresight analysis, the model further enables stress-testing of decisions under evolving policy and market conditions, ensuring resilience and adaptability. These practical linkages strengthen the novelty of the framework by demonstrating how methodological rigor translates into concrete, actionable outcomes.

2. Literature review

The development of sustainable CSCs for EV batteries requires overcoming a range of challenges across environmental, economic,

social, and governance dimensions. Table 2 lists the key sustainability challenges and matches them with relevant solutions, based on the literature studies. This section uses Table 2 as a guide to discuss each sustainability problem and explain the context, cause and the potential solutions more deeply.

2.1. Environmental sustainability dimensions

Environmental sustainability is a core principle in CSCs due to their serious environmental impacts (Aishwarya et al., 2025). Table 2 categorizes these challenges into three main groups such as environmental resource and lifecycle concerns (ERL), Circular recovery systems and material reuse (CRM), and sustainable materials and resource substitution (SMS). To tackle the challenges above, Table 2 provides several solutions including resource efficiency and optimization (S1), recycling and recover technologies (S 2), environmental impacts and sustainability management (S3), energy efficiency and green technologies (S4) along with material and battery design innovations (S5).

2.1.1. Environmental resource and lifecycle concerns (ERL)

ERL encompasses the unsustainable environmental demands resulting from the extraction, production, and disposal phases of EV batteries (Tang et al., 2019; Aishwarya et al., 2025). A significant sub-challenge is the scarcity and sustainability of critical materials (ERL 1). The manufacture of EV batteries depends on limited and geopolitically concentrated minerals such as lithium, cobalt, and nickel, whose extraction results in significant environmental repercussions, including deforestation, groundwater depletion, and toxic contamination (Sharma & Manthiram, 2020). The reliance on these resources renders the SC susceptible to disruption and elevates the environmental cost of battery manufacturing (Mota et al., 2015; Aishwarya et al., 2025). A significant concern is the emissions and impacts from production and manufacturing processes (ERL 2) (Petavratzi et al., 2022; Liu et al., 2023). Manufacturing processes are energy-intensive and predominantly reliant on fossil fuels, leading to considerable greenhouse gas emissions that compromise the net-zero objectives linked to EV adoption (Hantanasirisakul & Sawangphruk, 2023; Philippot et al., 2019). The management of EOL battery waste handling and recycling barriers (ERL 3) continues to be inadequately addressed in most emerging economies (Wasesa et al., 2022; Mu et al., 2023). In the absence of organized collecting systems, sophisticated recycling infrastructure, significant quantities of spent batteries are inappropriately discarded, resulting in the release of toxic compounds, including heavy metals and organic solvents, into the environment (Alfaro-Algaba & Ramirez, 2020; Narang et al., 2023).

Three principal strategies are identified as paramount to properly tackle the ERL problem. Initially, advancements in material and battery design innovations (S5) facilitate the implementation of low-impact chemistries, like sodium-ion and lithium–iron phosphate as well as modular battery topologies (Sharma & Manthiram, 2020; Dhairiyasamy et al., 2024). These innovations diminish reliance on limited resources, facilitate disassembly, and improve recyclability (Sharmili et al., 2023; Nguyen-Tien et al., 2022). Secondly, recycling and recovery technologies (S 2) are crucial in mitigating environmental risks linked to disposal (Qiao et al., 2024; Jiang et al., 2021). Advanced techniques, such as hydrometallurgical and direct cathode recycling, facilitate the extraction of high-purity critical materials, enhancing material circularity and minimizing environmental leakage (Ramoni & Zhang, 2013; Thomas & Mishra, 2024). Third, energy efficiency and green technologies (S4) can substantially diminish lifecycle emissions by decarbonizing battery manufacture using cleaner energy sources and better production techniques (Niri et al., 2024; Gebhardt et al., 2022). These measures collectively reduce the environmental impact of EV batteries, improve supply security, and match industrial practices with global sustainability objectives (Mathur et al., 2019; Tavana et al., 2023).

2.1.2. Circular recovery systems and material reuse (CRM)

CRM tackles the issues of extracting valuable materials from depleted EV batteries and reintegrating them into the SC (Chen et al., 2022; Steward et al., 2019). This challenge underscores the inefficiencies in the post-use stage of batteries (Steward et al., 2019; Aishwarya et al., 2025). A significant issue is the technological limitations in material recovery (CRM 1). Existing recycling systems frequently do not attain high recovery rates for essential materials like lithium and graphite, particularly when addressing newer, more intricate battery chemistries (Xiong et al., 2020; Barman et al., 2023). Additionally, there are inefficiencies in resource reclamation and utilization (CRM 2), as recovered resources are not properly reintegrated into manufacturing due to issues of purity, economic viability and conformity with production requirements (Alfaro-Algaba & Ramirez, 2020). Finally, gaps in infrastructure for reverse logistics and recycling systems (CRM 3) are particularly pronounced in emerging economies, where informal sectors predominantly manage battery handling, frequently lacking regulatory supervision or technical expertise (Wasesa et al., 2022; Vieceli et al., 2023).

To tackle these difficulties, the primary focus is on recycling and recovery technologies (S 2), which enhance material extraction efficiency and purity via improved methods adapted to changing battery chemistries (Bridge & Faigen, 2022; Yang et al., 2021). Secondly, advancements in material and battery design innovations (S5) provide design-for-disassembly and standardization, guaranteeing the compatibility of recovered materials with production inputs (Sharma & Manthiram, 2020; Picatoste et al., 2022). Ultimately, resource efficiency and optimization (S1) improve coordination in reverse logistics and facilitate predictive planning, reducing waste and assuring a more effective integration of recovered materials into production (Reinhardt et al., 2020; Sharmili et al., 2023). These technologies collectively enhance circularity, diminish reliance on raw materials, and foster a more robust EV battery ecosystem (Thomas & Mishra, 2024; Zhu et al., 2024).

2.1.3. Sustainable materials and resource substitution (SMS)

SMS underscores a critical design-level constraint in the EV battery value chain, the persistent reliance on non-renewable, high-impact materials, and the gradual shift towards eco-friendly alternatives (Thompson et al., 2021). The limitations in procuring eco-friendly or sustainable materials stem (SMS 1) from both technological inadequacy and economic compromises, as sustainable inputs are either insufficiently developed or too expensive (Ramoni & Zhang, 2013; Tavana et al., 2023). The poor management of crucial material SCs (SMS 2) exacerbates the inconsistent integration of lower-impact replacements into battery production, especially in markets lacking clear traceability systems (Gebhardt et al., 2022; Aishwarya et al., 2025). Ultimately, the minimal industrial adoption of sustainable and alternative material technologies (SMS 3) indicates a persistent dependence on traditional chemistries such as NMC and LCO, despite the availability of feasible alternatives (Parviziomran & Elliot, 2024; Das, 2024). This hesitance hinders innovation, confines SCs to high-risk materials, and obstructs initiatives aimed at alleviating environmental impact through material substitution (Nguyen-Tien et al., 2022; Qiao et al., 2024).

To address the challenges related to SMS, three solutions are particularly pertinent. Addressing SMS necessitates three separate interventions (Mu et al., 2023; Aishwarya et al., 2025). Innovations in material and battery design (S5) promote the use of low-impact alternatives such as solid-state or LFP batteries by integrating flexible, modular structures that minimize overall material consumption (Hantanasirisakul & Sawangphruk, 2023; Alfaro-Algaba & Ramirez, 2020). Environmental impact and sustainability management tools (S3) facilitate this transition by integrating lifecycle evaluations, environmental benchmarking, and green compliance requirements into material sourcing and product creation for promoting transparency and traceability (Qiao et al., 2024; Bruno & Fiore, 2024). Ultimately, resource efficiency and optimization (S1) enhance these initiatives by reducing

overall material input via systemic efficiency improvements, enabling enterprises to achieve sustainable objectives without sacrificing cost-effectiveness (Yang et al., 2021; Thomas & Mishra, 2024). Collectively, these solutions mitigate environmental impacts, foster innovation, and guarantee responsible material replacement (Liu et al., 2023; Chaianong et al., 2024).

2.2. Economic sustainability dimensions

Economic sustainability encompasses cost efficiency, resilience, and resource optimization within CSCs (Aishwarya et al., 2025). Table 1 classifies challenges into two groups supply network robustness and economic stability (SNR) along with operational sustainability and process integrity (OSP). Solutions like CE emphasis (S6) and strategic planning and decision-making (S7), SC and logistics optimization (S8) as well as market analysis and incentives (S9) are suggested to tackle these challenges (see Table 2).

2.2.1. Supply network robustness and economic stability (SNR)

SNR denotes the susceptibility of EV battery SCs to logistical disturbances, macroeconomic variances, and operational inflexibility (Mota et al., 2015; Bridge & Faigen, 2022). A fundamental difficulty lies in the structural vulnerability of SC architecture and logistics systems (SNR 1), where bottlenecks, insufficient visibility, and restricted geographical diversification render the SC prone to disruptions from events such as pandemics, natural disasters, political instability (Hantanasirisakul & Sawangphruk, 2023; Steward et al., 2019). Another factor pertains to vulnerability to economic shocks and market swings (SNR 2) volatile raw material prices and currency imbalances can significantly impact production costs, particularly for nations reliant on imports (Thompson et al., 2021; Liu et al., 2023). Moreover, operational constraints in SC technology and risk management (SNR 3) hinder enterprises capacity to foresee interruptions, improve routing, and adjust to demand variations, consequently prolonging lead times and diminishing overall responsiveness (Qiao et al., 2024; Bruno & Fiore, 2024).

Strategic planning and decision-making (S7) serve as a fundamental way to mitigate these economic vulnerabilities (Philippot et al., 2019; Steward et al., 2019). Scenario-based planning instruments, risk mapping, and supplier diversification methods empower organizations to anticipate uncertainty and transition from reactive to proactive SC management (Jiang et al., 2021; Thompson et al., 2021). SC and logistics optimization (S8) are equally crucial, concentrating on improving system-wide coordination, utilizing digital twin simulations, and deploying real-time visibility technologies to minimize inefficiencies and enhance responsiveness (Das, 2024; Parviziomran & Elliot, 2024). Collectively, these technologies facilitate the development of robust, flexible, and nimble supply networks that are more equipped to withstand economic volatility and sustain stability in the swiftly changing EV battery market (Bridge & Faigen, 2022; Steward et al., 2019). The market analysis and economic incentives (S9) improve SC stability by identifying vulnerabilities and giving targeted support like subsidies and tax breaks, strengthening weak areas (Barman et al., 2023; Tavana et al., 2023). This enhances both physical and economic resilience of the supply networks (Chaianong et al., 2024; Mu et al., 2023).

2.2.2. Operational sustainability and process integrity (OSP)

OSP tackles the inefficiencies as well as ethical deficiencies presented in the internal operations of EV battery production and processing systems (Thomas & Mishra, 2024; Nguyen-Tien et al., 2022). A fundamental problem is the deficiency in production efficiency (OSP 1);

Table 1
Comparative critique of literatures applying MCDM techniques.

Study	Domain	Weighting method	Ranking method	Stakeholder segmentation	Lifecycle coverage	Dual mapping (challenges and solutions)	Uncertainty handling	Scenario testing
Guler and Yomralioglu (2020)	EV fast-charging station	AHP / FAHP	TOPSIS	No	Infrastructure siting	Yes	Fuzzy only	No
Samvedi, Jain & Chan (2013)	Textile & steel industries	Fuzzy AHP	Fuzzy TOPSIS	No		Yes	Fuzzy only	No
Gebhardt et al. (2022)	EV battery	Delphi consensus		No	production, use	No	Crisp judgments only	No
Giri et al. (2024)	EV battery	Delphi	GTMA	No	reverse logistics	No	Crisp judgments	No
Aishwarya et al. (2025)	Indian EVBSC challenges/solutions			No	forward and reverse	Yes	None	No
Samaie et al. (2020)	EV policy prioritization	AHP weights	Fuzzy TOPSIS	No		No	Fuzzy	No
Tadić et al. (2025)	Green SC strategies	Delphi	AHP	No	Partial	No	Crisp only	No
Haktanır & Kahraman (2025)	EV battery strategies	Fuzzy AHP	Fuzzy VIKOR	No	Product-level	No	Yes (fuzzy sets)	No
Gouveia, et al. (2025)	EV recycling supply chains	Delphi		No	Reverse logistics	No	Crisp consensus	No
Abdullah et al. (2023)	Sustainable supplier selection (SMEs)	FAHP	FTOPSIS	No	Supply stage	Yes	Fuzzy	No
Wang, Dang & Nguyen (2021)	E-commerce reverse logistics	FAHP	FTOPSIS	No	Reverse logistics	Yes	Fuzzy	No
Nazam et al. (2015)	Sustainable supplier selection in avionics	FAHP	Fuzzy TOPSIS (ranked 8 suppliers)	No	Procurement/ supplier selection	Yes	Fuzzy	Yes
Belal et al. (2025)	EV battery SC			No	EOL	No	None	No
Parviziomran & Elliot (2024)	Battery value chain (socio-technical view)			No	System-level	No	None	No
Prajapati et al. (2021)	EV selection (consumer focus)	FAHP	TOPSIS	No	End-user	No	Fuzzy	No
Present study	EV battery supply chain	FAHP	FTOPSIS	Yes (six groups)	Full lifecycle, forward reverse	Yes	Fuzzy	Yes

Table 2
Sustainable circular supply chain practice challenges with criteria and sub-criteria.

Sustainability factors	Challenges		References	Solutions	Reference
	Criteria	Sub-criteria			
Environmental sustainability dimensions	Environmental resource and lifecycle concerns (ERL)	Scarcity and sustainability of critical materials (ERL 1)	(Tang et al., 2019); (Sharma & Manthiram, 2020); (Mota et al., 2015); (Petavratzi et al., 2022); (Hantanasirisakul & Sawangphruk, 2023); (Wasesa et al., 2022); (Narang et al., 2023); (Philippot et al., 2019); (Wellten et al., 2025); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)	Resource efficiency and optimization (S1)	(Mota et al., 2015); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Zhu et al., 2024); (Reinhardt et al., 2020); (Aishwarya et al., 2025)
		Emissions and impacts from production and manufacturing processes (ERL 2)		Recycling and recover technologies (S 2)	(Mathur et al., 2019); (Picatoste et al., 2022); (Hantanasirisakul & Sawangphruk, 2023); (Alfaro-Algaba & Ramirez, 2020); (Bridge & Faigen, 2022); (Narang et al., 2023); (Philippot et al., 2019); (Steward et al., 2019); (Sharmili et al., 2023); (Jiang et al., 2021); (Thompson et al., 2021); (Liu et al., 2023); (Chaianong et al., 2024); (Mu et al., 2023); (Yang et al., 2021); (Thomas & Mishra, 2024); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)
		EOL battery waste handling and recycling barriers(ERL 3)		Environmental impact and sustainability management (S 3)	(Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Hantanasirisakul & Sawangphruk, 2023); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Zhu et al., 2024); (Mathur et al., 2019),; (Picatoste et al., 2022); (Aishwarya et al., 2025)
	Circular recovery systems and material reuse (CRM)	Technological limitations in material recovery (CRM 1)	Chen et al., 2022); (Hantanasirisakul & Sawangphruk, 2023); (Steward et al., 2019); (Xiong et al., 2020); (Tang et al., 2019); (Alfaro-Algaba & Ramirez, 2020); (Wasesa et al., 2022); (Narang et al., 2023); (Chaianong et al., 2024); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Parviziomran & Elliot, 2024); (	Energy efficiency and green technologies (S 4)	(Hantanasirisakul & Sawangphruk, 2023); (Alfaro-Algaba & Ramirez, 2020); (Bridge & Faigen, 2022); (Narang et al., 2023); (Steward et al., 2019); (Sharmili et al., 2023); (Jiang et al., 2021); (Thompson et al., 2021); (Liu et al., 2023); (Chaianong et al., 2024); (Ramoni & Zhang, 2013); (Yang et al., 2021); (Thomas & Mishra, 2024); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)
		Inefficiencies in resource reclamation and utilization (CRM 2)	Barman et al., 2023); (Tavana et al., 2023); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)	Material and battery design innovations(S 5)	(Mota et al., 2015); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Zhu et al., 2024); (Reinhardt et al., 2020); (Mathur et al., 2019); (Picatoste et al., 2022); (Hantanasirisakul & Sawangphruk, 2023); (Alfaro-Algaba & Ramirez, 2020); (Bridge & Faigen, 2022); (Aishwarya et al., 2025)
		Gaps in infrastructure for reverse logistics and recycling systems (CRM 3)			
	Sustainable materials and resource substitution (SMS)	Constraints in sourcing eco-friendly or sustainable materials (SMS 1)	Thompson et al., 2021); (Liu et al., 2023); (Ramoni & Zhang, 2013); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Vieceli et al., 2023); (Aishwarya et al., 2025)		
		Ineffective critical material supply chain management (SMS 2)			
		Low industrial adoption of sustainable or alternative material technologies(SMS 3)			
Economic sustainability dimensions	Supply network robustness and economic stability (SNR)	Vulnerabilities in supply chain architecture and logistics security (SNR 1)	(Mota et al., 2015); (Bridge & Faigen, 2022); (Hantanasirisakul & Sawangphruk, 2023); (Steward et al., 2019), (Jiang et al., 2021), (Alfaro-Algaba & Ramirez, 2020); (Wasesa et al., 2022); (Narang et al., 2023); (Thompson et al., 2021); (Liu et al., 2023); (Das, 2024); (Parviziomran &	Circular economy emphasis(S 6)	(Narang et al., 2023); (Philippot et al., 2019); (Steward et al., 2019); (Sharmili et al., 2023); (Jiang et al., 2021); (Thompson et al., 2021); (Liu et al., 2023); (Chaianong et al., 2024); (Ramoni & Zhang, 2013); (Mu et al., 2023); (Yang et al., 2021); (Thomas & Mishra, 2024); (Vieceli et al., 2023); (

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Table 2 (*continued*)

Sustainability factors	Challenges		References	Solutions	Reference
	Criteria	Sub-criteria			
			Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)		Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)
		Susceptibility to economic shocks and fluctuations(SNR 2)		Strategic planning and decision making (S 7)	(Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Bruno & Fiore, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Aishwarya et al., 2025)
		Operational limitations in supply chain processes and logistics technologies (SNR 3)		SC and logistic optimization (S 8)	(Mathur et al., 2019); (Picatoste et al., 2022); (Hantanasirisakul & Sawangphruk, 2023); (Alfaro-Algaba & Ramirez, 2020); (Philippot et al., 2019); (Steward et al., 2019); (Sharmili et al., 2023); (Jiang et al., 2021); (Liu et al., 2023); (Yang et al., 2021); (Thomas & Mishra, 2024); (Aishwarya et al., 2025)
	Operational sustainability and process integrity (OSP)	Optimization of production and operational efficiency (OSP 1) Waste reduction and circular practices in manufacturing (OSP 2) Ethical compliance in sourcing and operations (OSP 3)	(Mota et al., 2015);); (Aishwarya et al., 2025); (Bridge & Faigen, 2022); (Hantanasirisakul & Sawangphruk, 2023); (Steward et al., 2019); (Jiang et al., 2021); (Alfaro-Algaba & Ramirez, 2020); (Wasesa et al., 2022); (Narang et al., 2023); (Thompson et al., 2021); (Liu et al., 2023); (Mu et al., 2023); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022)	Market analysis and economic incentives (S 9)	(Sharma & Manthiram, 2020); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Picatoste et al., 2022); (Hantanasirisakul & Sawangphruk, 2023); (Aishwarya et al., 2025)
Social sustainability dimensions	Human-centered and ethical risk dimensions (HER)	Labor exploitation, job safety, and fair employment (HER 1) Social and cultural disruption due to industrial activities (HER 2) Ethical dilemmas in raw material sourcing and EOL handling (HER 3)	Reinhardt et al., 2020); (Zhu et al., 2024); (Mathur et al., 2019); (Yang et al., 2021); (Picatoste et al., 2022); (Thomas & Mishra, 2024); (Nguyen-Tien et al., 2022); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Aishwarya et al., 2025)	Collaborative and stakeholder engagement(S 10)	(Aishwarya et al., 2025); (Alfaro-Algaba & Ramirez, 2020); (Bridge & Faigen, 2022); (Narang et al., 2023); (Philippot et al., 2019); (Steward et al., 2019); (Sharmili et al., 2023); (Jiang et al., 2021); (Thompson et al., 2021); (Liu et al., 2023); (Chaianong et al., 2024); (Mu et al., 2023); (Yang et al., 2021); (Thomas & Mishra, 2024); (Nguyen-Tien et al., 2022)
Governance sustainability dimensions	Technology scalability and infrastructure gaps (TSI)	Inefficient, costly, or outdated battery recycling methods (TSI 1)	Tang et al., 2019); (Mota et al., 2015); (Petavratzi et al., 2022); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Bruno & Fiore, 2024); (Vieceli et al., 2023); (Aishwarya et al., 2025)	Policy framework and compliance(S 11)	(Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Reinhardt et al., 2020); (Mathur et al., 2019); (Picatoste et al., 2022); (Hantanasirisakul & Sawangphruk, 2023); (Alfaro-Algaba & Ramirez, 2020); (Aishwarya et al., 2025)
		Non-standardized or unsafe battery collection/disposal processes (TSI 2)		Regulatory frameworks and safety compliance(S 12)	Bridge & Faigen, 2022); (Narang et al., 2023); (Steward et al., 2019); (Sharmili et al., 2023); (Jiang et al., 2021); (Thompson et al., 2021); (Liu et al., 2023); (Chaianong et al., 2024); (Yang et al., 2021); (Thomas & Mishra, 2024); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)
		Delayed or underfunded advancements in next-		Advanced monitoring and	(Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri

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Table 2 (*continued*)

Sustainability factors	Challenges		References	Solutions	Reference
	Criteria	Sub-criteria			
		gen battery technologies (TSI 3)		digital solutions(S 13)	et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Zhu et al., 2024); (Reinhardt et al., 2020); (Mathur et al., 2019); (Picatoste et al., 2022); (Aishwarya et al., 2025)
	Governance, standards, and regulatory alignment (GRA)	Weak enforcement of environmental and operational regulations (GRA 1) Lack of coherent national or regional battery-related policy frameworks (GRA 2) Absence of unified international standards and regulatory coordination(GRA 3)	(Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Aishwarya et al., 2025)	Technological and material innovations (S 14)	(Hantanasirisakul & Sawangphruk, 2023); (Alfaro-Algaba & Ramirez, 2020); (Bridge & Faigen, 2022); (Narang et al., 2023); (Philippot et al., 2019); (Steward et al., 2019); (Sharmili et al., 2023); (Jiang et al., 2021); (Thompson et al., 2021); (Liu et al., 2023); (Chaianong et al., 2024); (Mu et al., 2023); (Yang et al., 2021); (Thomas & Mishra, 2024); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)
	Digital integration for supply chain transparency (DIT)	Inadequate use of predictive analytics in battery lifecycle assessment (DIT 1) Weak real-time quality monitoring mechanisms in production or recycling(DIT 2) Limited implementation of blockchain or digital tracking in battery supply chains(DIT 3)	(Bridge & Faigen, 2022); (Alfaro-Algaba & Ramirez, 2020); (Wasesa et al., 2022); (Thompson et al., 2021); (Mu et al., 2023); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Das, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Vieceli et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)		
	Research-driven gaps and knowledge deficiencies (RGD)	Slow adoption and development of emerging technologies (RGD 1) Data unavailability and lack of robust methodological tools (RGD 2) Economic volatility affecting research and innovation funding (RGD 3) Insufficient international collaboration and knowledge transfer structures (RGD 4)	Petavratzi et al., 2022); (Gu et al., 2021); (Chen et al., 2022); (Zhang et al., 2021); (Yang et al., 2022); (Chaianong et al., 2024); (Ramoni & Zhang, 2013); (Wellten et al., 2025); (Dhairiyasamy et al., 2024); (Giri et al., 2024); (Gebhardt et al., 2022); (Jannesar Niri et al., 2024); (Qiao et al., 2024); (Bruno & Fiore, 2024); (Parviziomran & Elliot, 2024); (Barman et al., 2023); (Tavana et al., 2023); (Nguyen-Tien et al., 2022); (Aishwarya et al., 2025)		

numerous battery production lines function beneath optimal output owing to antiquated gear, erratic quality control, or excessive dependence on manual labor (Reinhardt et al., 2020; Zhu et al., 2024). This results in elevated expenses, postponements, and squandered resources (Tavana et al., 2023; Aishwarya et al., 2025). The difficulty of insufficient waste reduction and circular practices in manufacturing (OSP 2) is closely related, as production offcuts, rejected components, and non-recyclable wastes are not properly reintegrated into the value stream, resulting in environmental and financial detriment (Giri et al., 2024; Gebhardt et al., 2022). Moreover, ethical compliance in sourcing and operations (OSP 3) continues to be a significant issue, particularly in areas where labor norms, transparency, and environmental protections are inadequately enforced (Das, 2024; Parviziomran & Elliot, 2024). This not only subject's corporations to reputational risk but also compromises long-term sustainability goals (Thomas & Mishra, 2024; Wellten et al., 2025).

The emphasis on CE (S6) is essential for addressing these difficulties by integrating principles of reuse, remanufacturing, and resource looping into the production process (Wellten et al., 2025; Dhairiyasamy et al., 2024). This guarantees the minimization of waste streams and the reintegration of secondary materials into upstream industrial processes (Alfaro-Algaba & Ramirez, 2020; Narang et al., 2023). In conjunction with this, strategic planning and decision-making (S7), particularly via the implementation of lean management systems and operational key performance indicators, facilitates enterprises in optimizing production workflows, minimizing inefficiencies, and augmenting process control (Hantanasirisakul & Sawangphruk, 2023; Alfaro-Algaba & Ramirez, 2020). These technologies collectively enhance the operational framework of the EV battery SC, rendering it more efficient, transparent, and socially accountable (Parviziomran & Elliot, 2024; Barman et al., 2023). Along with this, another solution is promoting market analysis and economic incentives (S9) by aligning operational strategies with market trends and sustainability goals (Yang et al., 2021; Thomas & Mishra, 2024). This encourages circular practices and the adoption of eco-friendly technologies (Bridge & Faigen, 2022; Aishwarya et al., 2025).

2.3. Social sustainability dimensions

Social sustainability involves labor rights, ethical sourcing, and community impacts within EV battery CSCs (Tavana, et al., 2023). Table 2 highlights issues under human-centered and ethical risk dimensions (HER), linking these to solutions such as stakeholder

engagement (S 10).

2.3.1. Human-centered and ethical risk dimensions (HER)

HER highlights the sometimes-neglected societal implications of EV battery SCs, especially for raw material extraction, manufacture, and EOL processing (Tang et al., 2019; Aishwarya et al., 2025). A significant concern is the exploitation of labor and inadequate workplace safety (HER1) in many upstream industries, particularly artisanal mining and informal recycling in developing nations, exposing workers to hazardous situations without any protective rules as well as equitable remuneration (Mota et al., 2015; Jannesar Niri et al., 2024). This is exacerbated by the social and cultural upheaval resulting from industrial activities (HER 2), wherein mining and waste management operations displace communities, harm local ecosystems, and undermine social cohesiveness (Petavratzi et al., 2022; Bruno & Fiore, 2024). Finally, ethical difficulties in sourcing and disposal practices (HER 3) are common, especially when corporations get raw materials from war zones or dispose of battery trash in nations with less stringent environmental and labor regulations (Dhairiyasamy et al., 2024; Vieceli et al., 2023). These actions not only sustain social injustice but also damage the credibility and social license of the Ev sector (Gebhardt et al., 2022; Giri et al., 2024).

Collaborative engagement with stakeholders (S 10) is an effective technique to mitigate these problems (Yang et al., 2021; Thomas & Mishra, 2024). Companies can more productively align their operations with the demands and rights of impacted stakeholders (Tavana et al., 2023). These can be addressed by involving local communities, labor organizations, and civil society for decision-making process (Hantanasirisakul & sawangphruk, 2023). As reported by Bridge & Faigen (2022) and Steward et al. (2019), this strategy encourages transparency, cultivates trust, and generates social inclusive results. Stakeholder engagement tools allow for the early detection of social concerns and promote the collaborative development of fair labor policies and grievance procedures along with ethical sourcing standards (Sharmili et al., 2023; Liu et al., 2023). Social sustainability is increasingly recognized as a fundamental component of environmental, economic, social, and governance (EESG) performance (Aishwarya et al., 2025). This method guarantees that battery SC fulfils both technical and environmental goals while maintaining human dignity and equity throughout their life cycle (Chaianong et al., 2024; Mu et al., 2023).

2.4. Governance sustainability dimensions

Governance sustainability focuses on policies, technological innovations along with systematics analysis (Aishwarya et al., 2025). Table 2 outlines challenges under technology scalability and infrastructure gaps (TSI), governance, standards, and regulatory alignment (GRA), digital integration for SC transparency (DIT), and research-driven gaps and knowledge deficiencies (RGD). Table 2 also connects these to solutions like policy framework and compliance (S 11), regulatory frameworks and safety compliance (S12), advanced monitoring and digital solutions (S13), and technological and material innovations (S14).

2.4.1. Technology scalability and infrastructure gaps (TSI)

TSI represents a significant structural impediment in the advancement of circular EV battery SCs (Bridge & Faigen, 2022; Parviziomran & Elliot, 2024). Although technology solutions for battery recycling and repurposing are available, their scalability and economic sustainability across various regional contexts remain problematic (Das, 2024; Nguyen-Tien et al., 2022). A significant obstacle is the persistent utilization of ineffective or antiquated recycling methods (TSI 1), many of which cannot recover high-purity materials and adjust to changing battery chemistries (Bruno & Fiore, 2024; Vieceli et al., 2023). These inefficiencies constrain material recovery rates and elevate operational expenses. Moreover, non-standardized or hazardous collection and disposal methods (TSI 2) continue to exist in numerous areas, particularly where informal recycling prevails (Thompson et al., 2021; Qiao et al., 2024). This poses health and environmental hazards and interrupts steady material streams into formal recovery processes (Mu et al., 2023; Gebhardt et al., 2022). The slow rate of innovation and insufficient investment in next-generation battery technologies (TSI 3) further complicate matters (Wellten et al., 2025; Barman et al., 2023). This restricts the market presence of more sustainable, high-performance alternatives and hinders progress towards greener circular solutions (Dhairiyasamy et al., 2024; Giri et al., 2024).

Technological and material advancements are essential to overcome these limitations (Jannesar Niri et al., 2024). Besides the enhancement of recycling techniques (e.g., direct cathode or closed-loop systems), the establishment of scalable infrastructure is another development that can manage rising quantities of EOL batteries in a secure and standardized fashion (Liu et al., 2023; Aishwarya et al., 2025). Collaborations between government and industry, innovation incubators, and specialized R&D initiatives can expedite these advancements that guarantee recovery technologies aligning with swiftly evolving battery designs (Giri et al., 2024). Further, investments in infrastructure designed to align with regional capacities guarantee that circularity extends beyond advanced economies, becoming accessible and scalable in emerging markets (Mu et al., 2023). This method improves the capacity of EV battery SCs to function sustainably at scale by bridging the technology-infrastructure divide.

2.4.2. Governance, standards, and regulatory alignment (GRA)

GRA addresses the disjointed and uneven policy framework related to the manufacturing, utilization, and disposal of EV batteries (Petavratzi et al., 2022; Gu et al., 2021). A significant problem is the inadequate enforcement of environmental and operational regulations (GRA 1); several current policies lack legal authority is ineffectively implemented, permitting non-compliant actions to continue without repercussions (Chen et al., 2022; Zhang et al., 2021). The absence of cohesive national and regional battery-related policy frameworks is also problematic (GRA 2) (Yang et al., 2022; Bruno & Fiore, 2024). This leads to fragmented tactics among ministries, agencies, and sectors, undermining the advancement of cohesive CSC models (Chaianong et al., 2024). The lack of cohesive international standards and regulatory alignment (GRA 3) obstructs worldwide cooperation (Ramoni & Zhang, 2013; Aishwarya et al., 2025), especially in domains such as battery labeling (Tavana et al., 2023; Nguyen-Tien et al., 2022), traceability (Wellten et al., 2025), recycling efficacy (Dhairiyasamy et al., 2024), and safety adherence (Giri et al., 2024; Parviziomran & Elliot, 2024). In the absence of standardized norms, producers and recyclers encounter elevated compliance expenses and operational inefficiencies when traversing varied policy environments (Niriet al., 2024; Qiao et al., 2024).

To address these institutional and policy deficiencies, there is a need for a robust policy framework and compliance techniques (S 11) (Tang et al., 2019; Alfaro-Algaba & Ramirez, 2020). Governments can establish a regulatory framework that promotes circularity throughout the battery value chain (Aishwarya et al., 2025). This can be done by formulating comprehensive national policies that coincide with sustainability objectives (Aishwarya et al., 2025). This includes extended producer responsibility (EPR) (Dhairiyasamy et al., 2024), take-back mandates (Giri et al., 2024) as well as eco-design directives (Wellten et al., 2025). Simultaneously, regulatory frameworks and safety compliance systems (S12) are essential to enforce uniform safety, quality, and performance standards (Gebhardt et al., 2022). Especially for the handling, transportation, and recycling of spent batteries (Bruno & Fiore, 2024). These frameworks aid in standardizing practices (Parviziomran & Elliot, 2024; Mu et al., 2023), diminishing uncertainty (Barman et al., 2023), and enhancing cross-border collaboration (Zhu et al., 2024). Collectively, these governance-oriented solutions guarantee that sustainability concepts are integral components rather than supplementary elements within the legal and operational framework of

the EV battery business (Mathur et al., 2019; Hantanasirisakul & Sawangphruk, 2023).

2.4.3. Digital integration for supply chain transparency (DIT)

DIT denotes the insufficient use of digital tools that facilitate real-time tracking, data-informed decision-making, and comprehensive visibility throughout the EV battery SC (Mathur et al., 2019; Nguyen-Tien et al., 2022). A significant constraint is the inadequate use of predictive analytics in battery lifecycle assessment (DIT1) (Kumar et al., 2023). In the absence of dependable forecasting and diagnostics, stakeholders find it challenging to predict degradation trends, enhance second-life applications, schedule prompt recovery (Saeedi et al., 2024). A further issue is the weak real-time quality monitoring and control (DIT 2) in both production and recycling settings (Wellten et al., 2025; Das, 2024). This limits defect identification, diminishes operational responsiveness, and exacerbates quality variability (Dhairiyasamy et al., 2024). The limited implementation of blockchain and digital tracking systems (DIT 3) hinders traceability throughout the battery lifespan, from raw material procurement to disposal (Bruno & Fiore, 2024). The absence of transparency facilitates the perpetuation of unethical activities and undermines responsibility among SC participants (Tavana et al., 2023).

Resolving these difficulties requires the implementation of advanced monitoring and digital solutions (S13) (Wellten et al., 2025). Machine learning-driven predictive analytics can boost battery health forecasts and optimize EOL decision-making (Dhairiyasamy et al., 2024; Liu et al., 2023), while real-time monitoring technologies improve process control, minimize waste, and promote product uniformity (Thomas & Mishra, 2024). Moreover, blockchain systems offer unalterable records of material movements and ownership transitions, facilitating comprehensive lifecycle traceability and fostering trust among stakeholders (Nguyen-Tien et al., 2022; Sharmili et al., 2023). These technologies collectively enhance transparency, optimize risk management, and facilitate regulatory compliance, particularly in intricate, multi-actor SCs (Yang et al., 2021). Integrating digital intelligence across the EV battery value chain facilitates more sustainable, efficient, and socially responsible SC operations (Nguyen-Tien et al., 2022).

2.4.4. Research-driven gaps and knowledge deficiencies (RGD)

RGD denotes the systemic constraints in the creation, distribution, and utilization of evidence-based insights essential for the sustainable advancement of EV battery SCs (Agusdinata et al., 2018; Giri et al., 2024). A recurrent challenge is the slow adoption and development of emerging technologies (RGD 1) attributable to constrained research resources, significant risk aversion within the sector, and disjointed innovation ecosystems (Sharmili et al., 2023; Das, 2024). The lack of accessible and robust data (RGD 2) obstructs effective life cycle evaluation (Picatoste et al., 2022; Tavana et al., 2023), policy formulation (Jannesar Niri et al., 2024), and investment strategy (Hendrickson et al., 2015; Barman et al., 2023), especially in emerging economies with non-existent data infrastructure. Economic instability impacting research and innovation funding (RGD 3) further hinders advancement by diminishing the consistency and continuity of long-term R&D initiatives (Pellow et al., 2020; Qiao et al., 2024). Ultimately, insufficient international collaboration and knowledge transfer mechanisms (RGD 4) hinder the transnational dissemination of best practices, technical innovations, and sustainability frameworks (Hendrickson et al., 2015; Parviziomran & Elliot, 2024).

To address these interconnected deficiencies, policy frameworks and compliance mechanisms (S 11) are crucial for institutionalizing sustained public support for sustainability-oriented R&D, guaranteeing the availability of money and assistance for vital innovation sectors (Sharma & Manthiram, 2020; Wellten et al., 2025). Ultimately, technological and material innovations (S14), especially those designed for cost-effective, modular systems, can help to mitigate the gap between academic progress and practical implementation (Giri et al., 2024; Gebhardt et al., 2022). These solutions seek to establish a knowledge-intensive, well-coordinated innovation ecosystem that expedites the sustainable transformation of EV battery SC (Steward et al., 2019; Jiang et al., 2021).

2.5. Critiques of literature

The existing literature on sustainable CSC has made significant progress in identifying sectoral issues. However, a detailed review reveals key gaps, including fragmented approaches across sustainability dimensions, lack of prioritization frameworks, underutilization of advanced methodologies, and insufficient context-specific studies for emerging markets like India. Current efforts often address challenges in isolation, neglecting their interdependencies and the need for holistic integration. Table 1 illustrates the comparative critique of reviewed literatures applying MCDM techniques highlighting their methodological approaches, contributions, and limitations across circular and sustainable supply chain studies.

For example, Gebhardt et al. (2022) employed a thorough EESG-based sustainability framework derived from a literature study, expert interviews, workshops, and the Delphi approach. The study successfully brings together the expert opinions but doesn't give a clear structured quantitative ranking of problems or a systematic mapping of solutions. The lack of a defined multi-criteria evaluation model restricts its effectiveness as a decision support instrument in intricate SC contexts. Conversely, the FAHP-FTOPSIS paradigm improves methodological rigor by incorporating fuzzy logic to address expert uncertainty, doing consistency check to ensure weight reliability and systematically ranking both criteria (challenges) as well as solutions inside a structured MCDM framework. This dual-layered model converts experts' views into actionable priorities, rendering it more appropriates for policy development and adaptive planning.

Giri et al. (2024) utilized a Delphi technique to identify 19 barriers to sustainability and employed graph theory matrix analysis for ranking purposes. While GTMA provides a singular score-based ranking and integrated sensitivity analysis, it lacks the capability for stakeholder-specific segmentation and does not combine solution mapping. Furthermore, GTMA's dependence on precise numbers may trivialize the intrinsic uncertainty in expert assessments. This FAHP–FTOPSIS techniques exceeds this by allowing complex, fuzzy-based pairwise comparisons among stakeholder groups, which results in stakeholder-weighted rankings that more accurately represent contextual variations. Adding scenario-based analysis makes foresight-driven robustness testing, providing a more resilient and comprehensive decision-support system for building sustainable EV battery SC. Other research has looked at the problems with sustainability in a fragmented manner.

Aishwarya et al. (2025) presented a diverse linking of challenges and solutions in the EV battery CSC but they lacked an organized prioritization using MCDM methods which limit its quality of being relevant for practical decision-making. The unification of FAHP and FTOPSIS models advances systemic ranking for both criteria (challenges) and solutions strategies. This is used by expert driven fuzzy weights which improves the utility of research for execution and planning procedure. Belal et al. (2025) highlighted environmental and social hazards within EV SCs; but they were unsuccessful to present a structure, prioritized solution framework which constrained the study's empirical significance.

Parviziomran & Elliot (2024) used a socio-technical view to examine systemic hindrance in battery value chain. But the insights did not incorporate a formal prioritization method, and strategic implementations were not provided. This approach leverages systems thinking but interprets system-level issues into expert-prioritized rankings, which gives support with feasible solution pathways and stakeholder feedback. Guler and Yomralioglu (2020) applied AHP, FAHP, and TOPSIS for siting EV fast-charging stations, focusing on infrastructure location decisions. Samvedi, Jain and Chan (2013) employed FAHP and TOPSIS to evaluate risk and performance trade-offs in textile and steel industries demonstrating the ability of fuzzy MCDM to handle supply chain uncertainty. Wang et al. (2021) integrated FAHP and TOPSIS to prioritize

reverse logistics strategies in e-commerce, addressing sustainability in online retail operations. While these studies confirm the usefulness of fuzzy AHP and TOPSIS across diverse domains none incorporated stakeholder segmentation, lifecycle coverage beyond a single stage, or foresight and scenario testing which limits their generalizability to complex multi-stakeholder circular supply chains. Samaie et al. (2020) proposed Fuzzy TOPSIS to assess local EV policy in Tehran, providing a valuable foundation for municipal planning. However, their model was not incorporated with upstream methodologies such as FAHP, lacked stakeholder segmentation, and was not applicable to wider contexts. This research addresses this issue by employing FAHP for weight derivation, incorporating stakeholder-specific inputs, and testing across several scenarios to enhance scalability, making it scalable for national-level planning.

Prajapati et al. (2021) and Tadić et al. (2025) employed fuzzy MCDM approaches, specifically FAHP-TOPSIS with other methods, focusing solely on EV selection from the customer perspective, neglecting upstream SC issues and EOL considerations. This study expands the focus to comprehensive SC sustainability concerns, CE considerations, and incorporating EESG aspects, providing a strong analysis framework for sustainable battery SC. Likewise, Haktanır & Kahraman (2025) employed a fuzzy VIKOR technique to evaluate electric vehicle choices based on sustainability criteria. Their technique effectively identifies compromise solutions amidst conflicting criteria; nonetheless, it is predominantly designed for product-level decision-making and does not extend to supply chain-wide applicability. Moreover, it fails to incorporate circular economy (CE) aspects or perform stakeholder-based segmentation. In contrast, this framework prioritizes sustainability concerns throughout the entire EV battery SC, while also integrating fuzzy logic to address expert uncertainty, stakeholder-informed weighting, and a lifecycle-informed solution ranking. This facilitates comprehensive and policy-relevant decision support beyond the selection of end-user products.

Gouveia et al. (2025) employed a fuzzy TOPSIS model to assess sustainability performance in particular operational scenarios. Their method, while proficient in rating alternatives, emphasizes discrete options instead of systematically connecting upstream difficulties to downstream solutions. Furthermore, stakeholder diversity and the integration of the CE are not expressly considered. This study's system enhances by combining FAHP and FTOPSIS to initially establish challenge weights via expert consensus and fuzzy logic) and subsequently rank solution ideas, employing stakeholder segmentation and scenario-based sensitivity analysis. This dual-layer prioritizing facilitates more strategic, scalable, and context-sensitive planning. Ultimately, Abdullah et at. (2023) used an integrated FAHP-FTOPSIS technique to rank the challenges and strategies for sustainable manufacturing in Indian SMEs. Although the study is methodologically consistent with fuzzy MCDM approaches. They are limited to manufacturing SMEs and lack the sector-specific difficulties found in high-complexity value chains like EV batteries. Moreover, the dual ranking of barriers and strategies in provides decision-making assistance, it fails to combine stakeholder segmentations, lifecycle factors, and scenario-based forecasting. All of which are essential for EV companies, that involve multiple players and prolonged uncertainty. This method transcends traditional applications by customizing the FAHP-FTOPSIS technique for the EV battery CSC, by incorporating stakeholder group-level weight aggregation and performing scenario-based sensitivity analysis. This improves contextual relevance, accuracy of methodology, and policy applicability in dynamic and shattered SC setting.

As shown in Table 1, the reviewed studies demonstrate the versatility of fuzzy and related MCDM techniques across different contexts, yet they collectively reveal gaps and inconsistencies. Several works remain descriptive without prioritization, while others provide rankings that are not connected to actionable solutions. Lifecycle coverage is often restricted to single stages, stakeholder perspectives are generally overlooked, and foresight-based testing has not been attempted. To overcome these shortcomings, this paper develops a comprehensive FAHP–FTOPSIS framework tailored to the Indian EV battery supply chain. The framework identifies sustainability challenges, aggregates weights across stakeholder groups, and prioritizes solutions in a dual-layer structure that embeds foresight analysis for robustness under dynamic policy and market conditions. This design advances beyond prior methodologies by unifying weighting, ranking, stakeholder inclusion, and foresight within one model, thereby enhancing both academic rigor and practical policy relevance. The integrated challenge-solution (Table 2) ranking further strengthens coordinated planning across multiple sustainability parameters.

2.6. Stakeholder specific perspective on sustainability challenges

The sustainability challenges outlined in the previous sections affect stakeholders across EV battery SC in distinct ways. Recognizing these variations is crucial for both theoretical foundation and practical prioritizing. This study, informed by ST, examines six primary stakeholder groups: mining and resource extraction, raw material procurement, manufacturing and product development, SC and logistics, product management and strategy, and R&D. Each group functions at a distinct phase of the value chain and engages individually with environmental, economic, social, and governance concerns. The choice of six groups is grounded in both ST and Sustainability Theory. They represent conceptually distinct roles that are necessary and sufficient to capture the EV battery ecosystem (Farar, 2025; Hansen, 2025). Reducing the number of groups would omit essential perspectives, while expanding beyond six would fragment responsibilities and weaken analytical clarity. Prior mappings of SC ecosystems also confirm these six domains as fundamental to sustainability-oriented decision-making (Farar, 2025; Hansen, 2025). Understanding their perspectives facilitates more focused and inclusive solution strategies (Farar, 2025; Hansen, 2025).

Stakeholders in mining and resource extraction are immediately affected by difficulties associated with ERL and HER, especially regarding raw material scarcity, unsustainable extraction practices as well as labor safety issues (Domingues et al., 2024; Famiyeh, 2017). Raw material procurement entities face prominent exposure to SMS and SNR as they navigate volatile pricing, ethical sourcing requirements, and disruption in upstream availability (Hilend et al., 2023). Stakeholders in manufacturing and product development are widely impacted by OSP and TSI, focusing on improving process efficiency, fostering recyclability, and incorporating battery technologies (Pedgley, 2009).

SC and logistics stakeholders must address challenges related to SNR and DIT, given their role in material flow, real-time monitoring as well as logistics resilience (Liu et al., 2023). The product management and strategy teams are most concerned with CRM and SMS (Vachon and Klassen, 2006), as their decisions shape modularity, reusability, and long-term design compatibility with circular models (Vachon and Klassen, 2006; Wrålsen et al., 2021). R&D stakeholders are pivotal in engaging with RGD and technological innovations, contributing to material advancements, policy evaluations, and lifecycle-based assessments across the value (He, 2025; Svensson et al., 2018).

By integrating stakeholder viewpoints, the study ensures the prioritization of sustainability challenges and solutions accurately represents real-world complexity and operational variety (Ekmekcioğlu et al., 2021). The segmentation provides a clear foundation for applying multi-criteria decision-making methods that capture the trade-offs encountered by different actors. The six groups are deliberately structured to be mutually exclusive and collectively exhaustive, ensuring that no essential perspective is omitted and that roles and responsibilities are not duplicated. Broader classifications, such as dividing actors only into upstream and downstream, risk overlooking stakeholder-specific nuances, while overly fine classifications create redundancy and dilute analytical clarity. This balance establishes the six stakeholder categories as both conceptually rigorous and practically indispensable for sustainability-oriented decision-making in the EV battery ecosystem

(Farar, 2025).

3. Methodology

Fig. 2 visually shows the step-by-step model for applying sustainable CSC practices to EV batteries. This framework uses FAHP and FTOPSIS to rank challenges and solutions to handle the uncertainty and complexity in excerpt opinions. It's especially useful for India's diverse policy and market landscape. FAHP helps to turn vague human judgment into structured data. While FTOPSIS ranks the solutions options based on the closeness they are to the best possible outcome. Together, they provide a strong toll for making informed, context-centric decisions.

The adoption of an integrated FAHP–FTOPSIS methodology is motivated by the specific needs of this research. The sustainable CSC for EV batteries in India encompasses various stakeholders, qualitative expert contributions, and unpredictability in both policy and market conditions (Surange & Suthar, 2025). These complications require a methodological framework that can manage ambiguity, balance several criteria, and provide context-specific prioritization (Surange & Suthar, 2025). FAHP is appropriate for this context, as it encapsulates the ambiguity inherent in human judgment through fuzzy logic and enables systematic pairwise comparisons (Mane et al., 2025). It facilitates the transformation of qualitative ideas into measurable weights, which is crucial in areas devoid of dependable numerical data (Mane et al., 2025). Conversely, FTOPSIS proficiently evaluates solution possibilities by measuring their closeness to an optimal result, thereby elucidating complex, multi-objective decision-making contexts (Ghosh et al., 2021).

The integration of FAHP and FTOPSIS establishes a resilient and flexible decision-support system for assessing sustainability issues and prioritizing mitigation strategies (Wang et al., 2021). This methodology is especially pertinent in emerging nations such as India, where judgments must include regional inequalities, informal sector dynamics, and changing rules (Yadav et al., 2024). The integrated approach guarantees analytical precision and practical significance, facilitating informed, consensus-based decisions amidst uncertainty (Yadav et al., 2024). Its efficacy has been evidenced across various fields, such as logistics service provider assessment (Bayram, 2021), occupational healthcare prioritization (Chen, 2021), and water resource management (Noori et al., 2022), showcasing its adaptability in tackling intricate decision-making situations.

This study's methodological novelty is evident in three principal domains. Initially, it integrates FAHP and FTOPSIS into a dual-phase prioritizing framework that not only prioritizes issues (criteria and sub-criteria) but also assesses alternative solution strategies, an approach infrequently employed in the current EV battery SC literature. This approach is tailored for stakeholder-specific analysis, enabling distinct expert groups to evaluate and prioritize based on their unique perspective and roles within the SC. The study incorporates a predictive scenario-based sensitivity analysis that predicts potential shifts in solution rankings under varying future scenarios, offering a dynamic perspective for decision-making.

3.1. Research framework

The methodological foundation consists of three key stages as depicted in Fig. 2. Each stage builds sequentially on the prior, enabling in-depth evaluation of the sustainability issues and alternative strategies in the EV battery SC.

3.1.1. Identification of challenges and solutions

The challenges and solutions are amalgamated from an extensive literature review (Section 2) and validated through domain experts. A total of 50 sub-challenges (sub-criteria) were initially identified and

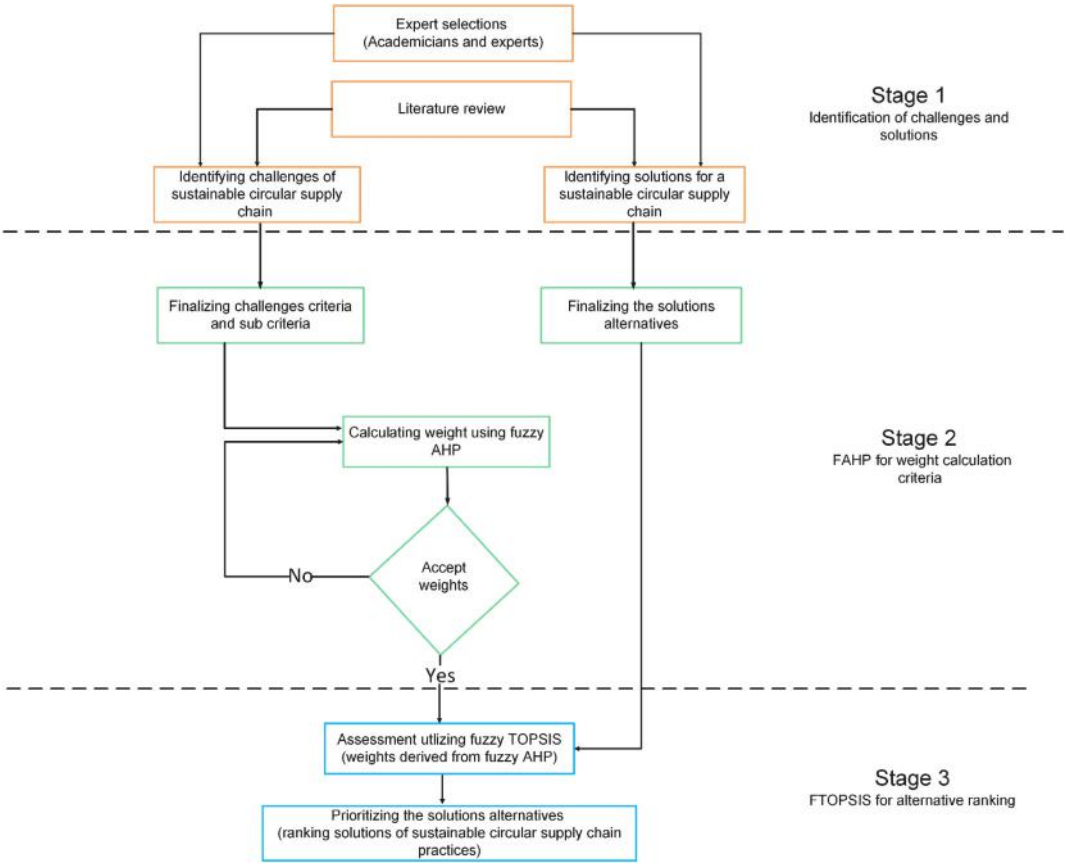

Fig. 2. Methodological framework of implementing sustainable CSC practices.

reduced to 35 sub-challenges (sub-criteria) after expert consultation (see section 3.3 and Appendix A).

3.1.2. FAHP for weight calculation criteria

FAHP was applied to derive the relative significance of the validated challenges and sub-challenges (sub-criteria) utilizing expert-based fuzzy pairwise comparison.

3.1.3. FTOPSIS for alternative ranking

FTOPSIS was used to evaluate and rank the solutions on their weighted performance across sub-challenges, considering their proximity to ideal solutions.

3.2. Identification of challenges and solutions

A comprehensive list of sustainability challenges and their related solutions was constructed through an extensive review of peer-reviewed literature relevant to EV battery SCs. The process led to the identification of 50 sub-challenges, covering EESG dimensions of sustainability (see Appendix A).

Subsequently, a series of expert consultations were conducted to validate, refine, and contextualize these issues based on the current industry practices and domain-specific priorities within the Indian EV battery sector. Based on the expert feedback, the number of sub-challenges was refined from 50 to 35 sub-challenges, ensuring clarity, relevance as well as non-redundancy. This refinement process increased the applicability and manageability of the evaluation framework. The finalized set of 35 sub-challenges was then categorized under the EESG model and used as the basis for FAHP pairwise comparisons and FTOPSIS evaluations. This curated and validated list is provided in Table 2.

3.3. Application of FAHP

Thomas L. Saaty was the first to develop this method for establishing a systematic practice for defining priorities and supporting complicated decision making (Forman & Gass, 2001). FAHP is an extension of the classic AHP technique through fuzzy logic, which captures the ambiguity and imprecision inherent in human judgments (Nazam et al., 2015). In most of the real work scenarios, there are certain decision facts that may be accurately assessed while others cannot (Meshram et al., 2019). Therefore, a fuzzy method was implemented to solve this issue (Prakash & Barua, 2015). The integration of fuzzy and AHP was introduced by (Chang, 1996), which utilizes TFN for pairwise comparison scale, and the approach is used for comprehensive extent (Fu et al., 2023).

Definition 1. *A fuzzy N on R is a TFN if its membership function μ_N (x): R → [0,1] and is defined as the following Eq. (1). The mathematical concept of fuzzy sets is taken from* (Kwong and Bai, 2003), (Sirisawat & Kiatcharoenpol, 2018), *and* (Ahmad & Qahmash, 2020).

$$\mu_N(x) = \begin{cases} 0 (x < e) \\ \dfrac{(x-e)}{(mv-e)} e \le x \le mv \\ \dfrac{(x-f)}{(mv-f)} mv \le x \le f \\ 0 (x > f) \end{cases} \quad (1)$$

From the equation (Eq. (1)), e ≤ s ≤ f, where e and f signify the lower and upper values, respectively, of fuzzy numbers N, and mv is the model value. The TFN can be represented by N=(e,mv,f).

(Fu et al., 2023). The technical laws of TFN are $N_1 = (e_1, mv_1, f_1)$ and $N_2 = (e_2, mv_2, f_2)$.

N_1 and N_2 are given in the following Eqs. (2)–(6) (Sirisawat & Kiatcharoenpol, 2018).

$$N_1 + N_2 = (e_1, mv_1, f_1) + (e_2, mv_2, f_2) = e_1 + e_2, mv_1 + mv_2, f_1 + f_2, \text{ for } e_1, e_2 > 0; mv_1, mv_2 > 0, f_1, f_2 > 0 \quad (2)$$

$$N_1 - N_2 = (e_1, mv_1, f_1) - (e_2, mv_2, f_2) = e_1 - e_2, mv_1 - mv_2, f_1 - f_2, \text{ for } e_1, e_2 > 0; mv_1, mv_2 > 0, f_1, f_2 > 0 \quad (3)$$

$$N_1 \text{ x } N_2 = (e_1, mv_1, f_1) \text{ x } (e_2, mv_2, f_2) = e_1 \text{x } e_2, mv_1 \text{x } mv_2, f_1 \text{ x } f_2, \text{ for } e_1, e_2 > 0; mv_1, mv_2 > 0, f_1, f_2 > 0 \quad (4)$$

$$N_1 \div N_2 = \frac{(e_1, mv_1, f_1)}{(e_2, mv_2, f_2)} = \frac{e_1}{f_2}, \frac{mv_1}{mv_2}, \frac{f_1}{e_2}, \text{ for } e_1, e_2 > 0; mv_1, mv_2 > 0, f_1, f_2 > 0 \quad (5)$$

$$N^{-1} = (e, mv, f)^{-1} = \left(\frac{1}{f}, \frac{1}{mv}, \frac{1}{e}\right) \quad (6)$$

To reflect the diverse opinions within EV battery SC, the FAHP was conducted separately for each of the six stakeholder groups. This stakeholder-specific approach enabled the identification of the challenges and sub-challenge priorities that are most relevant to each group's operational and strategic aims. The following steps are involved:

Step 1: Hierarchal model formation

Fig. 3 shows the aim, criteria (challenges) along with sub-criteria (sub-challenges) were organized into a hierarchical decision structure (see Fig. 3).

Step 2: Pairwise comparisons.

Experts from each stakeholder group conducted a pairwise assessment of criteria and sub-criteria using a nine-point fuzzy scale (Appendix B). Each criterion and sub-criterion were evaluated against others within the same criterion utilizing Triangular Fuzzy Numbers (TFNs) to encapsulate the intrinsic ambiguity in human judgment.

Step 3: Aggregation of judgments.

For each stakeholder group, the FAHP pairwise comparison matrices were aggregated using the geomean method. This step generated a collected fuzzy comparison matrix for each criterion, reflecting consensus across experts within the same group.

Comparing the decision makers (DMs) ratings. The outcome in comparison matrix eq (7) (u^k_{pq} is the rating of the k^{th} DM). Matrix is revised eq (8) and eq (9) that averages the rating of the k DMs (Ahmad & Qahmash, 2020).

$$\tilde{U}^k = \begin{bmatrix} \tilde{u}^k_{11} & \cdots & \tilde{u}^k_{1s} \\ \vdots & \ddots & \vdots \\ \tilde{u}^k_{s1} & \cdots & \tilde{u}^k_{ss} \end{bmatrix} \quad (7)$$

$$\tilde{u}^k_{pq} = \frac{\sum_{k=1}^{k} \tilde{u}^k_{pq}}{k} \quad (8)$$

$$\tilde{U} = \begin{bmatrix} \tilde{u}_{11} & \cdots & \tilde{u}_{1s} \\ \vdots & \ddots & \vdots \\ \tilde{u}_{n1} & \cdots & \tilde{u}_{ss} \end{bmatrix} \quad (9)$$

Step 4: Consistency comparison matrix

Consistency index (CI) is used to measure consistency in the verdicts of DMs in comparison matrix U.

At first, the average TFN in eq (8) is essential to convert into crisp numbers using (10), and this will lead to crisp comparison matrix U (Kwong and Bai, 2003).

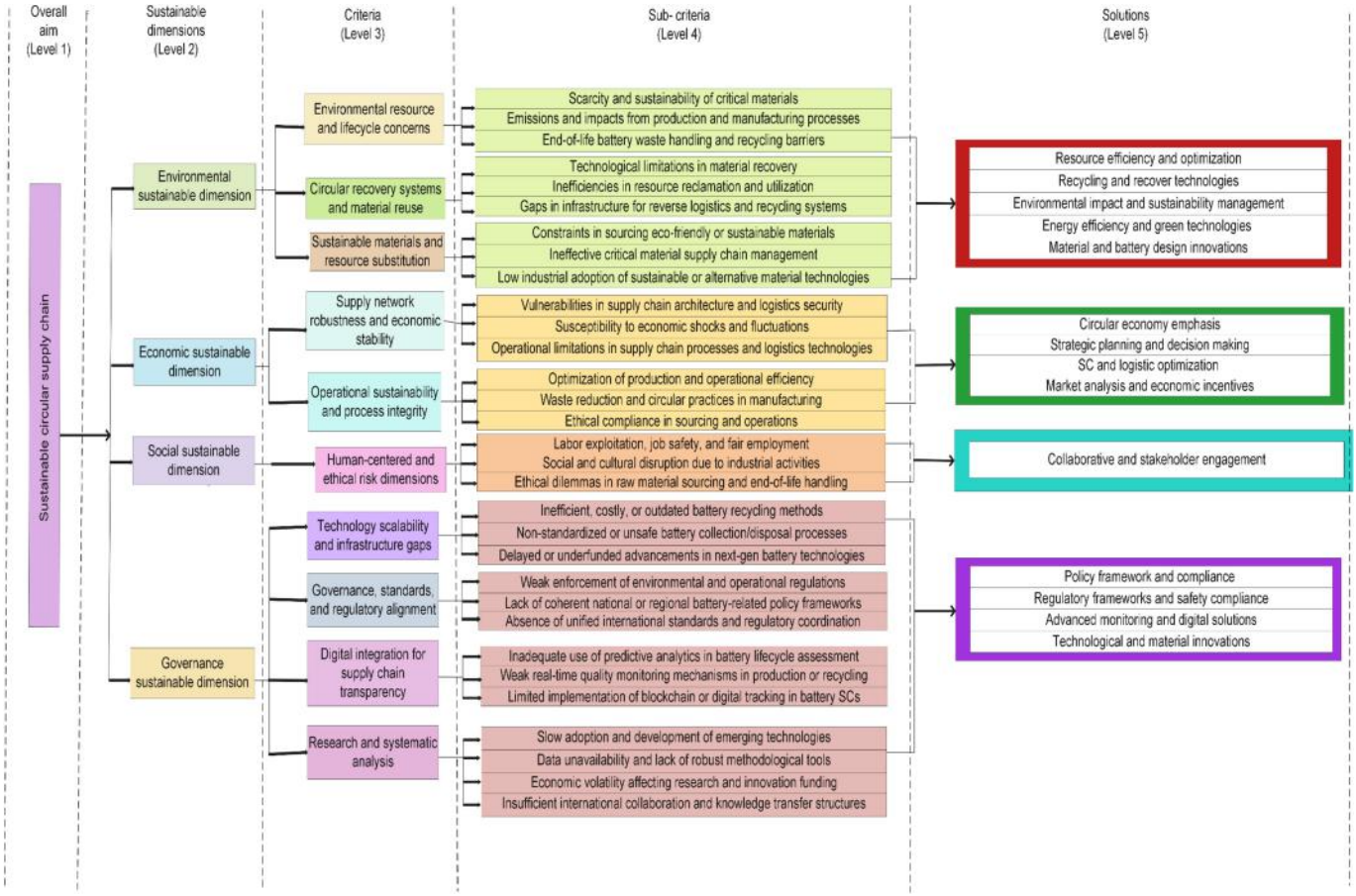

Fig. 3. Suggested research methodology for highlighting the challenges and solutions for sustainable CSC practices.

$$U_{pq}^{crisp} = \frac{a + 4b + c}{6} \tag{10}$$

where U_{pq}^{crisp} for any TFN $\tilde{U}$

The normalized principal eigenvector W, which shows normalized comparative weights for criteria, can be developed from U using eq (11). It is then the average row-wise value of a column-normalized matrix that is generated from U.

$$W_p = \frac{\sum_{q=1}^{s} \frac{u_{pq}}{\sum_{x=1}^{s} u_{xp}}}{s} \tag{11}$$

Subsequently, matrix X, which shows the weighted sum criteria, can be attained using eq (12).

$$X = UW \tag{12}$$

To make sure of the logical consistency of expert judgments, the CR was calculated separately for each stakeholder group's pairwise comparison matrix.

The extreme eigenvalue λ_{max} can be evaluated from eq (13), which is built on theorem $UW = \lambda W$ (Kwong and Bai, 2003).

$$\lambda_{max} = \frac{\sum_{p=1}^{s} \frac{x_p}{w_p}}{s} \tag{13}$$

The judgment matrix is examined consistently if the CR is below 0.1. CR is evaluated from eq (14) (Fu et al., 2023).

$$CR = \frac{CI}{RI} = \frac{\lambda_{max} - 1}{(n-1)RI} \tag{14}$$

where CI is the consistency index and RI is the random consistency index for the judgment matrix that can be produced from Appendix C. This step ensures that the relative judgments made by each group maintained internal coherence. All CR values were found to be within the acceptable threshold ($CR \leq 0.10$), conforming to satisfying the consistency across all stakeholder-specific matrices.

Step 5: Fuzzy geometric mean matrix is defined for attributes using (15) (Ahmad & Qahmash, 2020).

$$\tilde{z}_p = \left(\prod_{q=1}^{s} \tilde{u}_{pq} \right)^{1/s}, p = 1, 2, 3 \cdots\cdots s \tag{15}$$

Where each $\tilde{u}_{pq} = (e, mv, f)$ is a TFN.

$$\tilde{w}_p = \tilde{z}_p \otimes (\tilde{z}_1 \oplus \tilde{z}_2 \oplus \ldots\ldots \oplus z_n)^{-1} = \left(e\, w_p ,\ mv\, w_p,\ f\, w_p \right) \tag{16}$$

Here ew_p, $mv\ w_p$, $f\ w_p$ define the lower, middle and upper value of fuzzy weights of w_p.

De-fuzzy values for TFN are evaluated using the center of area method (centroid method) by using eq (17) and normalized using eq (18) (Ahmad & Qahmash, 2020).

$$Y_p = \frac{e_{w_p} + mv_{w_p} + f_{w_p} w_p}{3} \tag{17}$$

$$H_p = \frac{Y_p}{\sum_{q=1}^{s} Y_p} \tag{18}$$

Step 6: Validation of weights

The resulting weights were reviewed and validated by respective expert groups. These defuzzified and normalized, stakeholder-specific weights served as inputs for the FTOPSIS approach in the next stage of the analysis. This multi-stakeholder FAHP implementation gives a

comprehensive understanding of different actors in the EV battery SC perceive and prioritize sustainability challenges, developing the foundation for stakeholder-relevant solution ranking.

3.4. Application for FTOPSIS

Hwang and Yoon implemented FTOPSIS that analyzed the solutions based on the proximity to the optimal solution (NĂdĂban et al., 2016). The attribute selected must be determined at the shortest distance from the positive ideal solution and longest distance from the negative idea solutions (NĂdĂban et al., 2016). Kannan et al. (2009) pointed out that the traditional TOPSIS method isn't very good at dealing with uncertain data which is often the case in real-world situations particularly in sustainability studies where expert opinions can be vague or subjective. Due to these limitations, the FTOPSIS method was performed. FTOPSIS works better than the regular TOPSIS method in uncertain, complex decision-making context as mentioned by Liang & Meng (2019). To ensure the solution matched each stakeholder group's specific issues and priorities. So, the FTOPSIS analysis separately for each stakeholder group. This approach makes the evaluation of the alternatives more specific and accurate for each group, considering their priorities and sustainability goals. The technique follows a process from Sirisawat & Kitacharoenpol (2018) and Fu et al. (2023) is outlined below.

Step 1: Decision matrix development.

A stakeholder-driven decision matrix was carefully prepared, where each row represents a solution and columns denote thirty-five sub-criteria. Each entry in the matrix captures the perceived effectiveness of a solution in addressing a specific sub-criterion. This is done based on the expert rating using a 7-point linguistic scale (see Appendix D).

If a decision group with L members $D_1, D_2, D_3, D_4, \ldots D_L$ containing p alternative $A_1, A_2, A_3 \ldots, A_p$ with respect to q criteria $C_1, C_2, C_3, \ldots\ldots, C_q$

$$\begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_p \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots\cdots & C_q \end{array} \\ \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1q} \\ m_{21} & m_{22} & \cdots & m_{2q} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ m_{p1} & m_{p2} & \cdots & m_{pq} \end{bmatrix} \end{array} \tag{19}$$

where m_{pq} is the rating of the solution A_p in respect of criterion C_q.

Calculating the combined fuzzy rating for alternatives and the combined fuzzy weights for criteria.

The combined fuzzy rating $\tilde{x} = (a_{pq}, b_{pq}, c_{qp})$, of the p^{th} solution in respect to q^{th} criteria is acquired as outlined below:

$$a_{pq} = \min_L \left\{ a_{pq}^L \right\},\ b_{pq} = \frac{1}{L} \sum_{L=1}^{L} b_{pq}^L,\ c_{pq} = \max_L \left\{ c_{pq}^L \right\} \tag{20}$$

The aggregated fuzzy weight

$$w_{q1} = \min_L \left\{ w_{q1}^L \right\},\ w_{q2} = \frac{1}{L} \sum_{L=1}^{L} w_{q2}^L,\ w_{q3} = \max_L \left\{ w_{q3}^L \right\} \tag{21}$$

Step 2: Normalization of the matrix

The fuzzy decision matrix for each stakeholder group was normalized to transform the sub-criteria values into a comparable scale, ensuring consistency across different types of sub-criteria (benefits oriented) (NĂdĂban et al., 2016).

Evaluating the normalized fuzzy decision matrix. The normalized fuzzy decision matrix is

$$N = \left[\widetilde{m_{pq}} \right]_{s\,x\,t} \tag{22}$$

where p = 1,2,3,4,5,.., s and q = 1,2,3,4,5,…,t

$$\tilde{m}_{pq} = \left\{ \frac{a_{pq}}{c_q^*}, \frac{b_{pq}}{c_q^*}, \frac{c_{pq}}{c_q^*} \right\},\ c_q^* = \max_p \{ c_{pq} \} \text{ (benefit criteria)} \tag{23}$$

Step 3: Weight assigning

The weights derived from FAHP sub-challenges (sub-criteria) from each stakeholder group were applied to their normalized decision matrix. This step makes sure that the ranking of solutions reflects the relative importance of the sub-criteria as perceived by each stakeholder group.

Calculating the weighted fuzzy normalized decision matrix as depicted below:

$$\tilde{v} = \left[\tilde{v}_{pq} \right],\ \left[\widetilde{v_{pq}} \right]_{s\,x\,t},\ p = 1, 2, 3, 4, 5, .., \text{ s and q} = 1, 2, 3, 4, 5, \cdots, t;\ \text{where } \tilde{v}_{pq} = \tilde{m}_{pq} \times w_q \tag{24}$$

Step 4: Calculation of ideal solutions

For each stakeholder category, the FPIS and FNIS were determined. FPIS represents the best-case scenario, while FNIS represents the worst-case scenario (Sirisawat & Kiatcharoenpol, 2018).

Calculating the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS).

$$A^* = \left(\tilde{v}_1^*, \tilde{v}_2^*, \tilde{v}_3^*, \ldots . \tilde{v}_t^* \right),\ \text{where } \tilde{v}_q^* = \max_p \{ v_{pq3} \}; \tag{25}$$

$$A^- = \left(\tilde{v}_1^-, \tilde{v}_2^*, \tilde{v}_3^*, \ldots . \tilde{v}_t^* \right),\ \text{where } \tilde{v}_q^* = \max_p \{ v_{pq1} \} \tag{26}$$

Step 5: Distance calculation

The Euclidean distance of each solution from FPIS (d*) and FNIS (d^-) was calculated using standard fuzzy distance formulas (Fu et al., 2023). These distance measures show how close each solution is to the optimal and least desirable scenarios (Fu et al., 2023).

Calculating the distance of each alternative from FPIS and FNIS. The computation of distance $\tilde{d}_p^*$ and $\tilde{d}_p^-$ of each solution from A* and A^- is calculated as

$$d_p^* = \left\{ \sum_{q=1}^{t} \left(v_{pq} - v_{pq}^+ \right)^2 \right\}^{\frac{1}{2}},\ p = 1, ., s \tag{27}$$

$$d_p^- = \left\{ \sum_{q=1}^{t} \left(v_{pq} - v_{pq}^- \right)^2 \right\}^{\frac{1}{2}} \tag{28}$$

Step 6: Closeness coefficient and ranking

For each solution, the closeness coefficient (CC_p) was determined for each stakeholder group.

Computing the closeness coefficient CC_p for each alternative as given below,

$$CC_p = \frac{d_p^-}{d_p^- + d_p^*} \tag{29}$$

Then, the alternatives are ranked by their CC_p proximity to the optimal solution in descending order.

3.5. Advantages of the FAHP-FTOPSIS technique

The first benefit of the FAHP-FTOPSIS technique is its capability to encapsulate uncertainty, as fuzzy logic assists the lack of certainty in expert opinions by providing a more pragmatic representation of decision-making scenarios (Sirisawat & Kiatcharoenpol, 2018). This is especially useful in contexts where data is vague as well as subjective, providing a flexible and pragmatic technique (Kaya et al., 2019; Yilmaz & Ecemis Yilmaz, 2024). Moreover, incorporating FAHP-FTOPSIS

allows thorough prioritization by reviewing the relative significance of the criteria and the ranking of solutions (Ouma et al., 2015). FAHP systematically determines criteria weights, while FTOPSIS analyzes options based on their closeness to optimal outcomes by establishing an extensive and resilient decision-making model (Abdullah et al., 2023). This approach is well-suited to developing countries diverse EV markets which is characterized by rapidly evolving policies, informal recycling sectors, and varied stakeholder perspectives.

This methodology provides a robust framework for prioritizing challenges and solutions in the EV battery CSC. FAHP systematically calculates criteria weights, whereas FTOPSIS ranks solutions based on their proximity to ideal outcomes. Together, these methods address the inherent complexities of sustainable decision-making that offer actionable insights for policymakers and industry stakeholders.

4. Result and analysis

4.1. Data collection

As part of the initial stage, a pilot study was conducted with six domain experts from diverse stakeholder groups, including mining, manufacturing, procurement, logistics, product design, and academia. This pilot phase aimed to refine and validate the initial set of sustainability challenges, sub-challenges, and solution strategies drawn from an extensive literature review (see Appendix A). Initially, the framework consisted of 10 primary challenges, 50 sub-challenges, and 14 solution strategies. Based on the insights and critical feedback provided by these experts, the list was carefully revised to 10 challenges, 35 sub-challenges, and 14 solutions, ensuring greater clarity, relevance, and practical alignment with industry realities. This expert validation process helped enhance the conceptual accuracy and reduce redundancy across the criteria, laying the foundation for the subsequent structured data collection and analysis phases.

After the pilot study, primary data was gathered via a structured survey conducted by experts to guarantee empirical rigor and practical significance. The data collection sought to determine the relative significance of sustainability concerns and sub-challenges (for FAHP) as well as the performance assessments of solution methods (for FTOPSIS), facilitating a thorough and stakeholder-informed prioritization framework.

4.1.1. Expert panel and stakeholder classifications

Table 3 shows the distribution of 15 domain experts across stakeholder groups. Expert selection and stakeholder categorization were used as two distinct processes to ensure methodological rigor. Experts were selected based on their professional roles, academic credentials, and direct experience in the Indian EV battery ecosystem. After the selection, experts were classified into stakeholder groups based only on their current roles and functional responsibilities within their respective organizations. The role-based stakeholder segmentation ensured a grounded and context-specific understanding of the SC landscape.

To balance diversity with feasibility in a fuzzy multi-criteria setting, the panel was fixed at 15 experts. This size falls within commonly recommended ranges for expert-judgment MCDM (approx. 10–20) which are considered sufficient for stable aggregation while avoiding fatigue and inconsistency seen in very large panels (Samvedi et al., 2013; Kumar & Garg, 2017). Previous applications of fuzzy MCDM approaches, including FAHP and TOPSIS have also employed comparable panel sizes, studies like Kahraman et al. (2003) used 10 experts for supplier evaluation, Chen et al. (2006) applied FAHP with 12 experts for risk assessment. These precedents demonstrate that panels of this size are widely accepted as methodologically sufficient in fuzzy decision-making contexts. With approximately 2–3 experts per stakeholder group, all critical roles in the EV battery value chain were covered without diluting subgroup signals, ensuring judgments remained interpretable and auditable. The experts were classified into six stakeholder groups to represent different functional divisions of the SC. They are mining and resource extraction, raw material procurement, manufacturing and product development, SC and logistics, product management and strategies, and R&D. These categorizations enable a strong analysis by integrating the perspectives of both upstream and downstream actors, along with cross-cutting R&D stakeholders.

Table 3
Distribution of the 15 domain experts across stakeholder groups.

Stakeholders	Age	Gender	Education level	Years of experience (in years)	Position in the Organization
Mining and resource extraction	31	Male	Masters	9	Dy. Manager
	31	male	Masters	4+	Deputy Executive engineer
Raw material procurement	28	Female	BE	4	Technical and purchasing
	27	Male	BE	2	Procurement Executive
	42	Male	BE	18	Procurement Engineer
Manufacturing and product development	30	Male	BE	6	Design Engineer
	40	Male	PG	15	Senior Product Development Manager
Supply chain and logistics	27	Male	Masters	5	Lead supply chain
	33	Male	Post-Graduation	11	Senior Manager
	35	Male	Masters	12	Manager
	45	Male	Masters	21	Manager
Product management and strategy	35	Male	Masters	12	Senior Product Manager
	47	Male	Graduate	30	Senior program manager
Research and development	33	Male	PhD	8+	Asst. professor
	40	Male	PhD	7	Asst. professor

Exactly six groups were defined by mapping the EV battery lifecycle upstream, midstream, downstream, and cross-cutting innovation to distinct decision location that shape sustainability outcomes. This stakeholder segmentation is grounded in ST with heterogeneous power, legitimacy, and urgency and sustainability governance like environmental, economic, social, and institutional dimensions which together support analyzing roles separately rather than pooling them (Mitchell et al., 1997). The six-group design is therefore necessary and sufficient for fewer groups risk role omission and more groups would underpower subgroup analysis and reduce matrix reliability.

The selection of the six stakeholder groups was based on thorough linking of all stages and roles within the EV battery SC. This mapping process makes use of established research in the field. Additionally, input from industry experts was incorporated to guarantee practical relevance. This technique was designed to thoroughly represent all main operational and strategic segments relevant to sustainability in the Indian context. By including all the key stages of the SC from upstream (mining and raw material acquisition), midstream (manufacturing and logistics), downstream (product strategy and management) as well as interdisciplinary R&D, the study provides comprehensive representation of significant stakeholder categories involved in the EV battery SC. Employing such established practices strengthens the scientific rigor of

the study and enhances confidence that the perspectives collected accurately represent all relevant participants in the SC.

To maintain consistency and reduce bias during elicitation, four safeguards were implemented. First, each stakeholder group completed its own FAHP pairwise matrices and FTOPSIS ratings, preventing cross-group dominance and preserving role-specific priorities. Second, a common fuzzy linguistic scale was used and judgments within each group were aggregated using the geometric mean standard FAHP practice that down-weights outliers while preserving proportionality (Buckley, 1985; Kahraman et al., 2003). Third, every group matrix was screened for logical coherence using AHP's CR, enforcing CR $\leq$ 0.10 (Saaty and Katz, 1990) (see Table 3). Finally, weighting (FAHP) and ranking (FTOPSIS) were separated which reduces anchoring and confirmation bias and yields rankings driven by vetted weights (Kwong and Bai, 2003; Sirisawat & Kiatcharoenpol, 2018; Ahmad & Qahmash, 2020).

The choice of individual experts from each stakeholder group adhered to explicit eligibility criteria to guarantee domain relevance and informed judgment. All participants had a minimum of a bachelor's degree, with many holding postgraduate and doctoral credentials, ensuring a robust technical and academic foundation. Each expert also possessed at least two years of practical professional experience in the EV battery ecosystem, with the majority having between two and thirty years of experience, as outlined in Table 3. Their roles directly pertained to strategic, operational, or technical decision-making within their stakeholder areas, such as procurement, logistics, R&D, and manufacturing. These requirements ensured that the panel combined academic qualifications with practical experience, offering a comprehensive and representative viewpoint throughout the EV battery SC.

4.1.2. Expert survey

A targeted outreach effort was implemented to engage domain experts actively involved in the EV battery ecosystem, ensuring that the perspectives gathered in this study reflect real-world challenges and operational complexities. A total of fifty domain experts were initially contacted for participation via mail and professional networks. These experts were meticulously chosen based on their expertise in SC management, sustainability strategy, battery manufacturing, raw material procurement, and research in clean technologies.

Despite initial interest from numerous invites, only fifteen experts were able to fully participate in the research. This minimized response was primarily due to unavoidable circumstances like extensive travel commitments, time constraints, and health issues commonly related to senior professionals in industry and academia. However, the final experts panel was highly qualified and well distributed across the EV battery SC, making sure it was a diverse and representative sample.

Although the final panel comprised only fifteen experts which may be considered modest, several measures were undertaken to enhance the reliability of the results. The panel was carefully designed to ensure diversity across six stakeholder groups representing upstream, midstream, downstream, and cross-cutting functions of the EV battery supply chain. Strict eligibility criteria regarding expertise and professional experience further strengthened its quality. In addition, fuzzy logic was applied to capture uncertainty in judgments, pairwise consistency ratio checks were used to validate responses, and aggregation at the group level helped to mitigate potential individual bias (Sirisawat & Kiatcharoenpol, 2018). These steps ensured that the findings remain robust and stakeholder-representative despite the modest panel size.

The study used a two-stage engagement technique to comprehensively capture their insights.

- Structures questionnaire: A comprehensive and validated questionnaire was developed, designed to gather quantitative data utilizing a fuzzy linguistics scale for both FAHP and FTOPSIS (see Appendix E). The questionnaire was shared electronically with experts, and they were allotted adequate time to review, understand, and complete it. Follow-up reminders and clarifications were organized to guarantee the accuracy and completeness of the response.
- Semi-structured interview: Alongside the questionnaire, individual interviews were conducted with a selected group of experts and face-to-face. These interviews helped to validate the logic of response, clarified interpretations, and provided deeper qualitative insights that informed the final refining of the sub-criteria and the solution sets. This also fostered a collaborative environment. This engagement allowed experts to express stakeholder-specific nuances and evolving industry dynamics.

To ensure reliability, all questionnaire responses were examined for logical consistency, especially in the FAHP pairwise comparisons. Inconsistent inputs were addressed through direct follow-ups. Moreover, experts' opinions were consolidated at the stakeholder group level to reduce individual bias and ensure uniformity. Three senior domain experts representing manufacturing, SC, and R&D, were also extensively consulted. Their contributions were essential in evaluating, confirming, and restructuring the framework into 10 main criteria and 35 sub-criteria, ensuring contextual relevance and practical consistency. All the 15 experts engaged in both the FAHP and FTOPSIS stages, guaranteeing consistency and methodological alignment across the prioritization phases. This integrated framework provided the basis for FAHP based weighting methodology and the FTOPSIS-based ranking solution strategies.

4.2. Case study: Prioritizing sustainable practices in India's EV battery SC

This case study demonstrates the application of the FAHP-FTOPSIS framework to evaluate and prioritize challenges and solutions within India's EV battery SC. India presents a unique context due to its growing EV market, diverse socio-economic landscape, and reliance on informal recycling sectors. The case study illustrates how the methodology can guide policymakers and industry stakeholders in fostering a sustainable CSC.

4.2.1. Background and context

India's EV market is expanding rapidly, driven by regulations like the Faster Adoption and Manufacturing of Hybrid and EVs (FAME) scheme, and its commitment to net-zero emissions by 2070 emphasizes the strategic significance of changeover to electric adaptability within the wide territory's environmental aims (Singh et al., 2021). These initiatives' objective is to reduce dependence on fossil fuel and foster cleaner solutions in transport (Singh et al., 2021). India is developing and expanding its EV sector, but there are still serious problems that could slow or limit its success (Hema & Venkatarangan, 2022). The most vital challenges are that India does not produce enough of the essential raw material like cobalt, lithium and nickel, needed for EV batteries (Hema & Venkatarangan, 2022). Instead, it depends heavily on import which makes the country vulnerable to price fluctuations, dependent on foreign suppliers as well as risk from geopolitical or trade disruptions (Giri et al., 2024; Kala & Mishra, 2021).

At the same time, EOL battery management remains shattered, with a large share of utilized batteries handled by informal recyclers, without any environmental safeguards as well as occupational protocols (Tang et al., 2019). Many studies, like Du et al. (2018) and Santos et al. (2025), have reported unsafe dismantling practices, exposure to hazardous substance, and lack of accountability in material recovery process, raising serious.

environmental and social concerns. Furthermore, inefficient collection systems, limited investment in recycling infrastructure along with absence of standardized traceability mechanisms further hinder the development of a closed-loop system (Santos et al., 2025).

Given these challenges, this case study makes use of the FAHP-FTOPSIS framework to prioritize actionable solutions to adapt to India's unique needs. Unlike conventional evaluations, which often

overlook stakeholder diversity, this research incorporates expert's perspectives across multiple segments of the EV battery value chain, like mining, raw material procurement, SC and logistics, manufacturing strategy, and research.

4.2.2. Application of the framework

To systematically address the complexities within the Indian EV battery SC, this research adopts an integrated FAHP and FTOPSIS framework. This hybrid MCDM technique enables the evaluation and prioritization of sustainability challenges and the ranking of corresponding strategic alternatives.

Step 1: Identifying challenges and solutions.

The procedure began with an in-depth literature review followed by consultations with the domain experts to implement a list of relevant sustainability challenges and potential alternatives (see section 4.1). Based on this framework, ten criteria and 35 sub-criteria were identified across four sustainability dimensions of EESG (see Table 3). For solutions, fourteen potential solutions, including advanced recycling technologies, CE practices, and ethical sourcing frameworks, were mapped to these challenges (see Table 3).

Altogether, 15 experts were approached, each representing one of the stakeholder groups in the Indian EV battery ecosystems (see section 4.1.2). This collective expertise ensured a strong knowledge of real-world SC dynamics and policy implications.

Step 2: Criteria weight calculation using FAHP.

The FAHP approach was performed to evaluate the relative importance of the key challenge and sub-criteria, with assessments provided across six stakeholder groups. For each group, expert inputs were aggregated and processed as outlined in Section 3.4 followed to construct and analyze a fuzzy pairwise comparison matrix.

The FAHP approach was performed to evaluate the relative importance of the key challenge and sub-criteria, with assessments provided across six stakeholder groups. For each group, expert inputs were aggregated and processed to construct a fuzzy pairwise comparison matrix, with the aggregated matrices reported in Appendix F. To illustrate the computational procedure, the mining and resource extraction group is presented as a representative case in Appendix G. Specifically, the fuzzy geometric mean was calculated using Eq. (15), followed by defuzzification through Eq. (17), normalization using Eq. (18), and verification of consistency through Eqs. (13) and (14) (see Appendix G). Afterwards, fuzzy weights of each variable are evaluated using eq (17) as suggested by Buckley, (1985). To verify the reliability of expert judgments, CR were computed for each stakeholder group following Eqs. (13) and (14) (see Appendix G). Table 4 reports the corresponding CI and CR values for the six stakeholder-specific FAHP matrices. Specifically, CR values ranged from 0.061 (raw material procurement) to 0.099 (research and development), with mining and resource extraction (0.096), manufacturing and product development (0.097), supply chain and logistics (0.095), and product management and strategy (0.090) also falling within the acceptable range (see Table 4). Rom Table 4, it can be noted that all CR values were below the accepted threshold of 0.10, thereby confirming the logical coherence and robustness of the pairwise comparisons used in the analysis.

Because the weight Wp computation process is the same, the weights for the rest of the criteria along with the results of pairwise comparison for both criteria and sub-criteria. Fig. 4 depicts the weights of challenges across different stakeholder categories. Table 5 shows the global weight of criteria across different stakeholder categories. Table 6 shows the global weight of sub-criteria across different stakeholder categories.

Table 4
Consistency index (CI) and consistency ratio (CR) values for stakeholder-specific FAHP matrices at the criteria level.

Stakeholder group	CI	CR
Mining and resource extraction	0.142631	0.095725
Raw material procurement	0.091413	0.061351
Manufacturing and product development	0.144488	0.096972
SC and logistics	0.141568	0.095012
Product management and strategy	0.133444	0.089559
Research and development	0.147976	0.099312

The results indicate that ERL ranked highest among the criteria for the mining and resource extraction group (weight = 0.3125). This indicates a strong focus on environmental accountability and adherence to rigorous regulatory standards. The sub-criterion ERL 1 (scarcity and sustainability of critical materials) consistently received the highest ranking among all stakeholder groups, underscoring a shared acknowledgment of the environmental hazards linked to upstream operations like mineral extraction and processing. ERL was significantly represented in the rankings for product management and strategy along with R&D, indicating that regulatory rigor is perceived not merely as a compliance requirement but also as a catalyst for innovation and responsible product design. These findings correspond with ST, which advocates for integrated systems thinking and responsible stewardship in environmental domains.

Conversely, SNR has emerged as the foremost priority for stakeholders in raw material procurement, SC and logistics, and product management, routinely attaining the first or second place. SNR 1 (vulnerabilities in SC architecture and logistics security) emphasizing social resistance, community displacement, and local unrest consistently emerged as one of the most significant sub-criteria. This illustrates the tenets of ST, highlighting the necessity of addressing social fairness, inclusiveness, and consensus in project execution to prevent operational interruptions and uphold the social license to operate.

The GRA criterion was ranked second for mining and resource extraction and third for R&D stakeholders. The sub-criterion GRA 1 (weak enforcement of environmental and operational regulations) is frequently ranked inside the top five across all categories, particularly among upstream entities. This highlights the importance of dependable access to high-quality raw materials, crucial for maintaining the technological and economic feasibility of battery production and supply stability. In a similar vein, TSI received the highest ranking from the R&D group (weight = 0.302), with TSI 1 (inefficient, costly and outdated battery recycling methods) recognized as a crucial facilitator of industry-wide quality assurance, interoperability, and expedited technological adoption.

In contrast, DTI and RGD received the lowest weights among most groups, especially within the raw material procurement and manufacture and product development sectors. Sub-criteria such as DIT 3 (limited implementation of blockchain or digital tracking in battery SCs) and RGD 4 (insufficient international collaboration and knowledge transfer structures) consistently ranked among the lowest three, indicating that while these factors may have long-term strategic ramifications, they are not currently regarded as pressing operational issues. It is significant that the R&D group attributed moderate importance to RGD 1 (slow adoption and development of emerging technologies) and DIT1 (inadequate use of predictive analytics in battery lifecycle assessment), indicating a subtle acknowledgment of their relevance for future governance and traceability frameworks, a notion also reflected in the long-term perspective of Sustainability Theory.

An intriguing divergence is noted with OSP, which received the highest ranking from the manufacturing and product development group (weight = 0.289). The sub-criterion OSP 1 (optimization of production and operational efficiency) was the most significant globally within this criterion, indicating the manufacturing sector's heightened awareness of physical risk and liability during production processes. Conversely, other stakeholder groups assigned diminished rankings to OSP, signifying a disparity in perceived vulnerability to operational risks.

This FAHP-based prioritization provides a detailed, stakeholder-focused perspective on the intricate challenges associated with the sustainable implementation of CSC for EV batteries. It affirms that stakeholder roles, capacities, and exposures significantly impact their

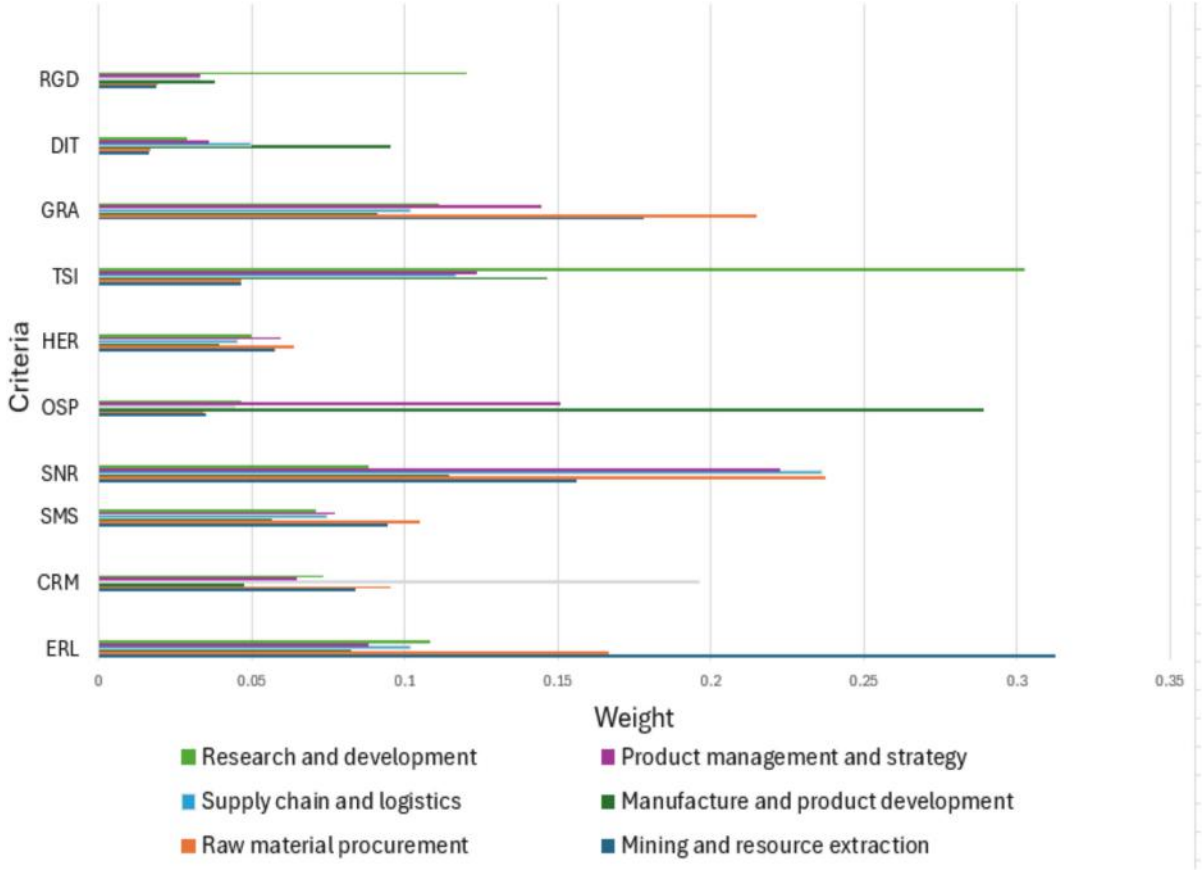

Fig. 4. Criteria weights of different stakeholder groups.

Table 5
Criteria weights for different stakeholder groups.

Sustainability impacts	Criteria	Mining and resource extraction	Raw material procurement	Manufacture and product development	Supply chain and logistics	Product management and strategy	Research and development
Environmental impacts	ERL	0.312485	0.166767	0.082245	0.101651	0.088062	0.108073
	CRM	0.083724	0.095216	0.047686	0.195966	0.064508	0.073484
	SMS	0.094612	0.10503	0.056521	0.07478	0.077097	0.071022
Economic impacts	SNR	0.156251	0.237286	0.114263	0.236045	0.222485	0.088257
	OSP	0.035254	0.034304	0.289237	0.04458	0.150986	0.046386
Social impacts	HER	0.057455	0.063842	0.039436	0.045562	0.059264	0.050095
Governance impacts	TSI	0.046754	0.046534	0.146471	0.11681	0.123622	0.302385
	GRA	0.177948	0.215039	0.091048	0.101989	0.144734	0.11135
	DIT	0.016543	0.016714	0.095203	0.049745	0.036	0.028777
	RGD	0.018974	0.019268	0.03789	0.032872	0.033243	0.120171

assessment of sustainability priorities. These insights underscore the necessity for a multi-tiered governance framework supported by both ST and Sustainability Theory that harmonizes economic performance, environmental integrity, and social welfare. The FAHP results serve as the foundational basis for the solution ranking analysis conducted via Fuzzy TOPSIS and elaborated upon in the subsequent step 3.

Step 3: Solution ranking using FTOPSIS.

To enhance the FAHP-based prioritization of challenges, the Fuzzy TOPSIS method was utilized independently for each of the six stakeholder groups to assess and rank 14 potential solutions according to their distinct perspectives and priorities.

The computation of the aggregated fuzzy decision matrix of solution the Eq. (20) is used. From Eq. (23), the benefit criteria are chosen. This study takes all the sub-criteria as benefit criteria into consideration. Then, normalize the fuzzy decision matrix of the solution by using Eq. (23). The weights derived from the FAHP approach in stage 2 are utilized for determining the weight of the fuzzy normalized decision matrix for solution using Eq (21). Since the study considered criteria as benefit, it is defined as FPIS A*(1,1,1) and FNIS as A^- (0,0,0). Subsequently, the distance between FPIS and FNIS is computed using Eq. (27) and Eq. (28). Eq (29) gives the CC_p for each stakeholder group that is presented. Consequently, the CC_p values are utilized in the last ranking of solutions for sustainable CSC practices across each stakeholder group (see Appendix H).

Fig. 5 shows examination of solution outcomes uncovers significant disparities and remarkable consistencies in different stakeholder group priorities. Mining and resource extraction consistently yielded elevated CC_p values across multiple solutions, with S12 (regulatory frameworks

Table 6
Sub-criteria for different stakeholder groups.

Criteria codes	Sub-criteria codes	Mining and resource extraction	Raw material procurement	Manufacture and product development	Supply chain and logistics	Product management and strategy	Research and development
ERL	ERL 1	0.209233	0.108751	0.056646	0.066289	0.058964	0.077324
	ERL 2	0.076232	0.04255	0.018603	0.025936	0.021483	0.022419
	ERL 3	0.027019	0.015466	0.006997	0.009427	0.007614	0.00833
CRM	CRM 1	0.04691	0.068066	0.02724	0.140087	0.043273	0.048581
	CRM 2	0.018042	0.017746	0.017735	0.036524	0.01499	0.016745
	CRM 3	0.018772	0.009404	0.002711	0.019355	0.006245	0.008158
SMS	SMS 1	0.030743	0.067814	0.036711	0.04829	0.053338	0.043079
	SMS 2	0.020632	0.026846	0.013863	0.018171	0.017862	0.019374
	SMS 3	0.043238	0.01037	0.005947	0.008319	0.005897	0.00857
SNR	SNR 1	0.096719	0.152511	0.077424	0.144125	0.148307	0.061209
	SNR 2	0.041235	0.057825	0.025254	0.068476	0.052742	0.019102
	SNR 3	0.018297	0.02695	0.011585	0.023444	0.021435	0.007945
OSP	OSP 1	0.022238	0.024026	0.201304	0.027265	0.111713	0.033451
	OSP 2	0.008761	0.006518	0.059132	0.011482	0.022922	0.007733
	OSP 3	0.004255	0.00376	0.0288	0.005834	0.016351	0.005203
HER	HER 1	0.035604	0.045154	0.026114	0.028861	0.04343	0.033543
	HER 2	0.015532	0.011998	0.009769	0.01266	0.01025	0.012221
	HER 3	0.006319	0.00669	0.003553	0.004041	0.005584	0.004332
TSI	TSI 1	0.035697	0.030154	0.096899	0.0793	0.089716	0.21848
	TSI 2	0.006567	0.011097	0.036248	0.024679	0.021747	0.054901
	TSI 3	0.00449	0.005283	0.013325	0.012832	0.012159	0.029003
GRA	GRA 1	0.099109	0.150415	0.060964	0.069843	0.101194	0.072336
	GRA 2	0.064629	0.044091	0.022212	0.021633	0.031362	0.029181
	GRA 3	0.01421	0.020533	0.007873	0.010512	0.012179	0.009833
DIT	DIT 1	0.012185	0.011459	0.04802	0.031732	0.026395	0.019694
	DIT 2	0.002877	0.003676	0.030932	0.013709	0.006219	0.00665
	DIT 3	0.001481	0.001579	0.010635	0.004304	0.003386	0.002433
RGD	RGD 1	0.011529	0.011523	0.019112	0.018562	0.003139	0.066633
	RGD 2	0.003896	0.004272	0.012311	0.007522	0.004852	0.028729
	RGD 3	0.00235	0.002164	0.004233	0.004655	0.007883	0.017614
	RGD 4	0.001199	0.001309	0.002235	0.002132	0.017368	0.007195

and safety compliance) (CC_p = 0.82), S 11 (policy framework and compliance) (CC_p = 0.75), S1 (resource efficiency and optimization) (CC_p = 0.70), and S 10 (collaborative and stakeholder) (CC_p = 0.67) identified as the highest-performing solutions. These findings underscore the paramount importance that mining stakeholders assign to regulatory compliance, resource management, and economic stability. This indicates an acknowledgment of the essential requirement for explicit rules, efficient resource management, and conducive market mechanisms as basic components for a sustainable and secure raw material SC.

Solutions such as S 11 (policy framework and compliance) and S 10 (collaborative and stakeholder engagement) routinely garnered elevated CC_p scores from various stakeholder groups. This cross-stakeholder alignment signifies their broad appeal and practical importance, suggesting a collective stakeholder agreement on the need for strong regulatory frameworks and proactive economic incentives as essential facilitators for circular sustainability.

Product management and strategy, in conjunction with R&D stakeholders, prioritized solutions such as S7 (strategic planning and decision making) (CC_p = 0.59) and S5 (material and battery design innovations) (CC_p = 0.56). This discovery highlights their fundamental significance as catalysts for innovation and sustainable circular business strategies. The notable ranking of solution S5, especially among R&D stakeholders, distinctly corresponds with the imperative to perpetually innovate, enhance material utilization, and incorporate developing technologies into battery lifetime management.

Conversely, solutions such as S 2 (recycling and recovery technologies), S6 (CE emphasis), and S8 (SC and logistic optimization) consistently obtained lower CCp values (about 0.51) among various stakeholder groups. The diminished ranks may signify present infrastructural constraints, technological obstacles, or transient economic issues, suggesting that these solutions may not be immediately feasible within India's current SC framework. Nonetheless, these solutions are crucial for long-term sustainability goals, a viewpoint further validated by their diverse performance in potential future scenarios during the sensitivity analysis.

The prioritization outcomes are highly aligned with the theoretical frameworks underpinning this study. From ST's viewpoint, the observed discrepancies in stakeholder preferences underscore the imperative for a pluralistic and collaborative approach to sustainability planning, wherein varied stakeholder requirements and objectives are meticulously reconciled. From the perspective of Sustainability Theory, the consistently elevated rankings of environmental and resource management solutions, such as S1, alongside regulatory-focused solutions like S

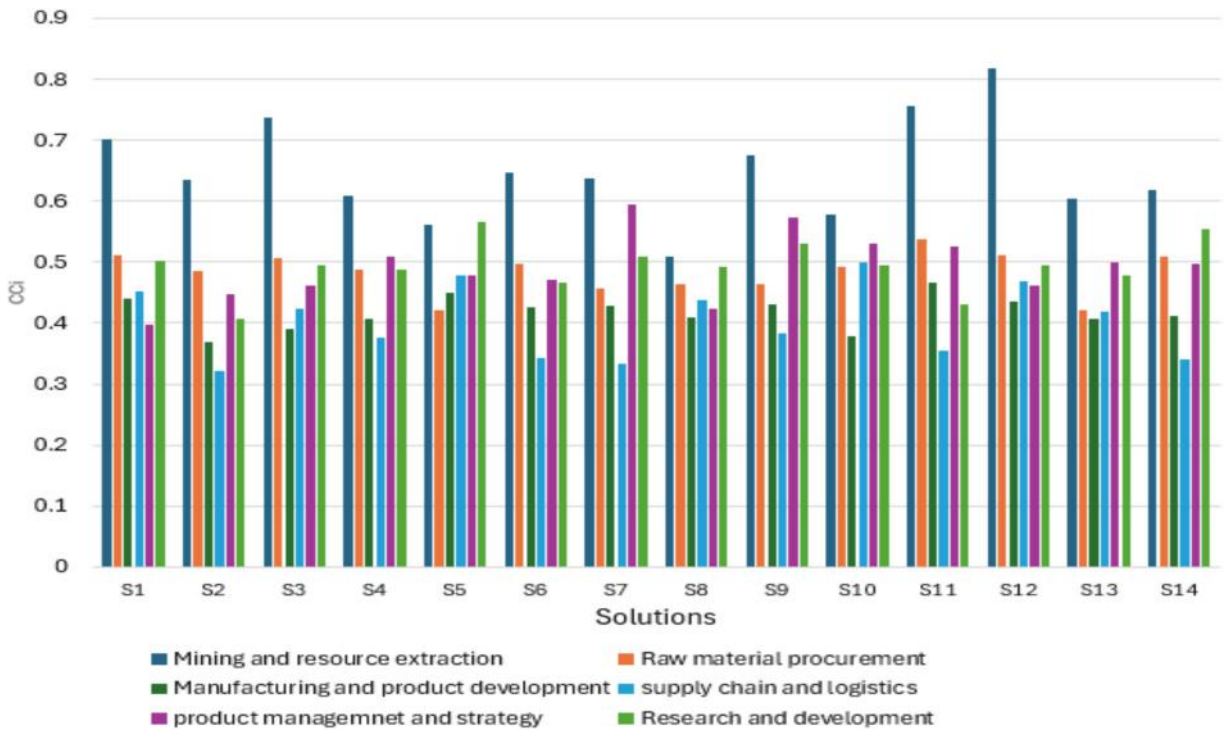

Fig. 5. Closeness coefficient (CCp) values for the proposed solution across six stakeholder groups in EV battery CSC.

11 and S12, reflect a fundamental comprehension and prioritization of solutions that provide both environmental stewardship and economic viability.

Furthermore, the results distinctly emphasize strategic domains where policymakers, industry executives, and academia can jointly concentrate their resources and innovative endeavors. Immediate policy measures and economic incentives can be customized to address solutions such as S 11, S12, S1, and S 10, while long-term infrastructural and

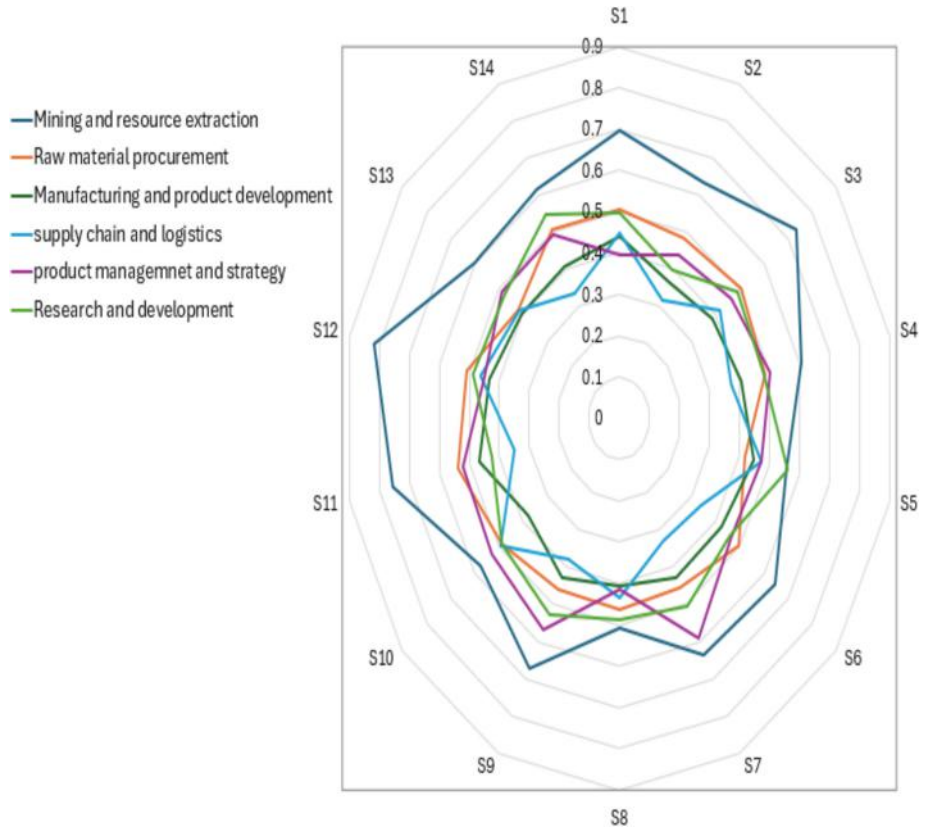

Fig. 6. Stakeholder-based sensitivity analysis under scenario 1: India achieves full circular battery ecosystems.

technological developments should strategically aim to progressively improve the viability and effectiveness of solutions like S 2, S6, and S8.

4.3. Sensitivity analysis

The scenario-based sensitivity analysis was performed to assess the robustness and adaptability of the solution prioritizations. This method facilitates the examination of how stakeholder preferences and solution rankings evolve in response to future uncertainties. Two divergent scenarios for the year 2040 were formulated: Scenario 1: India attains a comprehensive circular battery ecosystem, and Scenario 2: India confronts global SC instability and import reliance. These scenarios model India's transition routes, from leading in domestic battery circularity to increased dependence on unstable global SCs. The predictive sensitivity analysis of the EV battery industry given hypothetical lithium availability in India by 2040 is based on two scenarios, respectively (see Appendix I and J). Figs. 6 and 7 represent radar diagrams of the stakeholder-based sensitivity analysis under two scenarios, respectively.

In Scenario 1, India has established a comprehensive circular battery ecosystem, drawing inspiration from countries such as China, with a significant focus on manufacturing and product development, as well as R&D players, each with a weight of 20 %. This signifies an innovative-centric atmosphere prioritizing modularity, localized design, and sophisticated recycling capabilities. In this context, solutions including S 11 (policy framework and compliance), S 10 (collaborative and stakeholder engagement), S5 (material and battery design innovations), and S14 (technological and material innovations) have been identified as leading performers among stakeholders such as R&D, manufacturing, and strategy. For example, R&D assigned S14 a CC_p value of 0.5495, above its main result value of 0.5553. Likewise, S5 received prioritization from other sectors, including mining and resource extraction (0.5569), SC and logistics (0.4731), and R&D (0.5606), signifying its extensive systemic significance within a developed circular framework.

In Scenario 2, depicting a future in which India encounters global trade disruptions, raw material shortages, and insufficient domestic infrastructure, the weights were reallocated, and raw material procurement (25 %) and SC and logistics (20 %) attained critical significance. In this import-dependent scenario, the emphasis transitioned to operational resilience, highlighting S 10, S9 (market analysis and economic incentives), and S6 (CE emphasis). These solutions attained relatively elevated CC_p values in Scenario 2 among raw material procurement and SC and logistics stakeholders. For instance, SC and logistics assigned S 10 a CC_p of 0.4926, an increase from 0.4989 in the primary result, but raw material procurement marginally raised its score for S9 from 0.4634 to 0.4579, indicating perceived significance despite minor numerical fluctuations.

Upon comparing these situations with the primary FTOPSIS results, some significant observations emerge. The solutions S1, S 11, and S12, already ranked highly in primary study, retained their superior status in both scenarios, demonstrating their consistent strategic significance irrespective of external factors. Nonetheless, slight fluctuations in rankings, exemplified by the enhancement of S14 under R&D in Scenario 1 (from 0.5553 to 0.5495) and the persistent significance of S9 and S6 under Scenario 2 for procurement and logistics, illustrate that contextual dynamics profoundly affect stakeholder choices. Furthermore, the sensitivity analysis underscores the convergence of ST and sustainability theory in this research. ST is seen in the varied weights and preferences allocated by each group according to their distinct roles and risks along the SC. The theory of sustainability underpins the foresight-based methodology, emphasizing the necessity for long-term adaptability and systemic resilience against environmental and geopolitical risks. Collectively, these theories affirm the significance of dynamic prioritization models in facilitating sustainable transitions.

The sensitivity analysis validates the robustness of specific strategic options (e.g., S1, S 11), while indicating that policy formulation, economic flexibility, and innovation potential require ongoing evaluation as contextual circumstances change. These findings provide policymakers and business leaders with a decision-making framework that anticipates future disruptions while addressing stakeholder-specific needs. The evaluation designated changing the weightage of responsiveness across these alternatives using FTOPSIS. From Fig. 5, it can be noted from the analysis that S14 and S6 are the most effective alternatives within these scenarios, aligning with the FTOPSIS results providing strong support to the prioritization of these solutions, which ensures that the sectors can be prepared for the anticipated increase in demand and incorporation of the latest resource flow, such as nationally sourced lithium that increases sustainability as well as market resilience by 2040. These outcomes from the evaluations present a notable strategic decision making by providing a clear way for aiming for funds and development attempts in the sector.

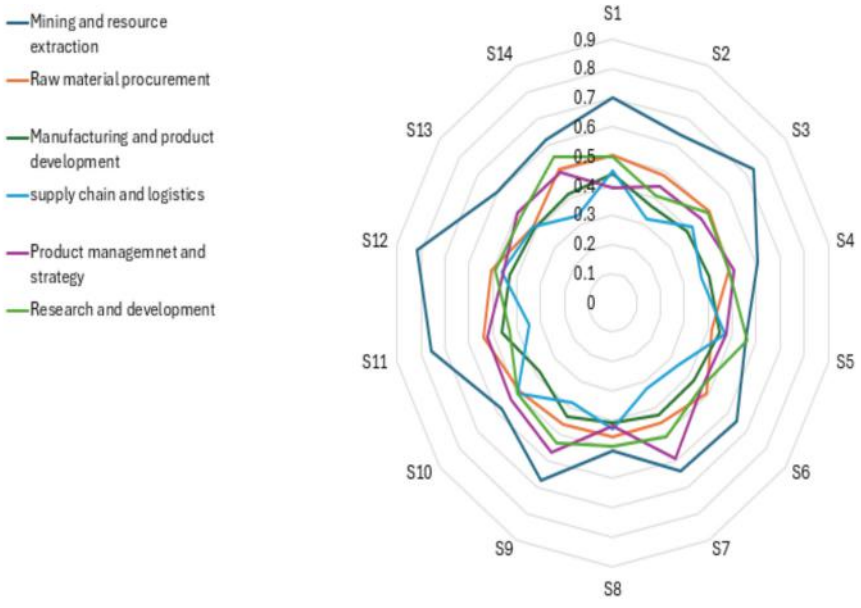

Fig. 7. Stakeholder-based sensitivity analysis under scenario 2: India faces global supply chain volatility & import dependence.

To explore the strategic development of India's EV battery SC amid unknown future trajectories, two feasible scenarios for the year 2040 were formulated: Scenario 1: circular ecosystem; Scenario 2: import reliance. These scenarios were crafted to illustrate boundary circumstances that embody diverse trajectories influenced by varying degrees of policy enforcement, technological progress, and SC robustness. Scenario 1 posits the effective implementation of CE concepts, significant investment in battery reuse and recycling infrastructure, and enhanced localization of essential material supply. This pathway corresponds with various current governmental initiatives, including the Faster Adoption and Manufacturing of Hybrid and EVs (FAME II) scheme (Kohli, 2024) and the Battery Waste Management Rules 2022, which enforce Extended Producer Responsibility (EPR) and promote battery end-of-life processing (Corpzo, 2023). This scenario also assumes that reverse logistics and processing infrastructure. This evolution will be supported by future technologies, such as AI-driven tracking and blockchain-enabled traceability systems (NITI Aayog, 2022).

In contrast, scenario 2 highlights the ongoing structural limitations, where domestic recycling and manufacturing capabilities remain underdeveloped. India relies heavily on importing critical raw materials like lithium, nickel and cobalt. This situation is made more difficult due to Indian's policy and regulations are not strictly enforced, especially around sourcing, handing and lagging behind the developing and expanding of EOL processing systems. These issues are underscored by the concerns expressed in national evaluations over India's dependence on international SCs for crucial minerals and the fragmented state of its existing recycling framework (Aishwarya et al., 2025; NITI Aayog, 2022).

The assumptions underpinning both scenarios were corroborated through a triangulated methodology. They were first assessed using worldwide forecasts, including the international energy agency's global EV outlook 2024, which outlines different trajectories for EV battery SC transitions paths based on geopolitical and industrial context (International Energy Agency (IEA), 2024). The scenarios were evaluated and assessed for plausibility by the same panel of 15 experts during the FAHP and FTOPSIS processes experts from academia, industry, logistics, raw material procurement, and policy provide practical insights on the feasibility, constraints, and interdependencies of each scenario. The design drew on a comparative review of similar transitions in the EU and China (Jiang et al., 2021). This showcase both high-circularity and import-dependent approaches (Jiang et al., 2021; Wesselkämper et al., 2024).

To guarantee the process was thorough and clear, the scenario analysis was implemented followed by a structure and refining it multiple times. The important factors and unknowns that could affect the scenarios were first found through comprehensive review of relevant policy documents, industry data as well as research papers. Early versions of the scenarios were created and presented to a panel of 15 experts from different domains like academia, industry, logistics, raw material sourcing along with governments. The validation process helps two rounds of interactive sessions where the experts critically analyzed and discussed each scenario's internal consistency, plausibility, and relevance to Indian's changing EV battery systems. After each round, surveys were used to collect both quantitative assessment and qualitative feedback. This feedback was systematically incorporated to refine the scenarios narrative and underlying assumption until consensus was achieved.

Rather than predicting outcomes, the scenarios serve as exploratory instruments to evaluates the resilience of strategies and priorities perform during uncertainty. They highlight the potential convergence or divergence of policy direction, technology capacity, and industry preparedness over the time. This helps decision-makers in designing more resilient and adaptive SC strategies.

5. Discussion

This section analyzes the primary findings of the study, outlines both theoretical and practical implications, and identifies the study's limits while suggesting opportunities for future research. It amalgamates stakeholder-specific insights with scenario-based foresight to deliver a thorough roadmap for enhancing sustainability in India's EV battery CSC.

5.1. Summary of key findings

The study employed a dual-stage FAHP–FTOPSIS methodology to evaluate and prioritize sustainability concerns and associated solution strategies across the Indian EV battery SC. The FAHP findings indicated that sustainability priorities differ markedly among stakeholder groups. Experts in mining and resource extraction highlighted environmental resource and lifecycle (ERL) concerns, especially the depletion of essential materials, whereas procurement and logistics professionals focused on supply network resilience (SNR), considering weaknesses in sourcing and transportation infrastructures.

The sub-criteria rankings revealed a common apprehension regarding upstream environmental deterioration and midstream operational inefficiencies, with significant emphasis placed on ERL 1 and SNR 1. The FTOPSIS research placed S12 (regulatory frameworks), S 11 (policy compliance), S1 (resource optimization), and S 10 (collaborative engagement) as the foremost solutions, especially from the viewpoints of mining and strategy stakeholders.

The scenario-based sensitivity analysis indicated that these solutions maintained high priority despite fluctuating future situations. Scenario 1 (circular ecosystem) and scenario 2 (import reliance) resulted in context-specific fluctuations in the rankings of solutions such as S14 and S6, highlighting the necessity for adaptation in planning. These findings provide a stakeholder-segmented and future-oriented framework for enhancing circularity and sustainability in India's EV battery SC.

5.2. Implications

5.2.1. Theoretical implications

This study enhances ST by empirically illustrating that sustainability objectives in the EV battery SC are diverse and significantly shaped by stakeholder roles, risk exposure, and operational emphasis. Stakeholders across mining, procurement, logistics, strategy, and research demonstrated varied preferences in recognizing and prioritizing sustainability concerns and solutions. This discovery substantiates the fundamental tenet of ST, which asserts that organizations must account for the diverse interests of all stakeholders impacted by their activities (Donaldson & Preston, 1995; Phillips, 2003). The varied responses among stakeholder groups correspond with (Mitchell et al., 1997) stakeholder salience model, emphasizing the necessity of integrating power, legitimacy, and urgency into sustainable decision-making frameworks. Thus, the study endorses the case for pluralistic, contextually aware methodologies in sustainability governance and policy formulation.

The paper asserts the imperative of incorporating ecological integrity, economic viability, and social responsibility into strategic planning from the standpoint of Sustainability Theory. The persistent emphasis on solutions such as S1 and S 11 among various stakeholder groups indicates a developing consensus on principles congruent with the triple bottom line framework. These findings also reflect the perspective proposed by (Dyllick & Hockerts, 2002), who underscored that sustainable development necessitates organizations to transcend mere compliance and adopt a proactive, system-oriented approach. The implementation of the hybrid FAHP–FTOPSIS methodology enhances this theoretical contribution by demonstrating how organized expert judgment, when integrated with scenario-based foresight, may translate abstract sustainability concepts into real decision-making contexts. The study validates core theories and illustrates a systematic approach for

integrating multi-stakeholder interests with long-term sustainability goals.

5.2.2. Practical implications

The FAHP–FTOPSIS framework advances practical application by linking ranked sustainability priorities to specific decisions and policies (Sirisawat & Kiatcharoenpol, 2018). For managers, the results provide structured guidance on resource allocation, such as determining whether investments should focus on supplier diversification, process efficiency improvements, or collaborative recycling partnerships. For policymakers, the framework supports evidence-based choices in designing interventions, for example deciding between prioritizing incentives for large-scale recycling facilities or strengthening digital tracking systems for battery traceability. In addition, the foresight-based scenario analysis enables authorities to test the robustness of these interventions under alternative market and policy conditions, ensuring that strategies remain adaptive as technologies, regulations, and stakeholder expectations evolve. The proposed FAHP- FTOPSIS framework delivers tangible benefits to a range of stakeholders by converting excerpts assessments into prioritized sustainability goals and actionable solutions. These insights are particularly beneficial for managers, policymakers, and researcher seeking to establish a resilient and circular EV battery SC in India.

5.2.2.1. Implication for managers. The model offers a structured decision-support instrument that integrates operational enhancements with sustainability objectives. Manufacturing and product development executives should prioritize methods such as S1 and S5 to improve production efficiency and mitigate environmental impacts. Procurement and logistics managers can address the sub-criterion SNR 1, which identifies vulnerabilities in raw material sourcing, hence facilitating more resilient and varied supplier networks. The implementation of stakeholder-weighted prioritization allows supply chain managers to customize decisions according to their functional roles, facilitating targeted and department-specific planning. Collaborative solutions like S 10 provide effective means for inter-organizational alignment, enhancing the adaptability of SCs to external disruptions and regulatory modifications.

These insights are especially pertinent for companies facing heightened regulatory demands concerning circularity, waste minimization, and the localization of supply chains. The model offers practical strategies for synchronizing internal decisions with external compliance requirements, including the Battery Waste Management Rules and the suggested extended producer responsibility (EPR) framework (Ministry of Environment, 2022). It additionally facilitates strategic planning within national industrial initiatives that promote domestic battery manufacturing and the localization of SCs. Utilizing the proposed framework enables managers to fulfil legal requirements while also achieving a competitive edge through enhanced design, sourcing, and cooperation strategies that are robust, scalable, and centered on sustainability.

5.2.2.2. Implication for policymakers. The paper presents evidence-based recommendations for formulating regulatory frameworks that promote circularity in the EV battery market. The prioritized solutions can be seamlessly integrated into national strategies, particularly the advocacy for S 11 and S12, which collectively establish the basis for a circular battery economy. The prioritization results developed using stakeholder viewpoints and fuzzy logic which helps to justify specific policy decisions. Additionally, scenario-based analysis allows policymakers to test the resilient of regulations under different future situations. This supports the creation of flexible and inclusive policies.

This model helps in creating a long-term policy for transport and industry that focuses on recycling, reducing imports and adopting green technologies. It supports national programs like FAME II, India's CE action plan as well as the battery incentive scheme. Decision-makers can use the framework to justify steps like supporting local recycling and promoting battery reuse based on stakeholder priorities. This framework facilitates better policy making which is inclusive and forward-looking, thereby enabling the evaluation of multiple factors and future scenarios.

5.2.2.3. Implications of researchers. This paper presents new ways to improve research methods and practical approaches in the field of sustainability. The paper shows the fuzzy MCDM techniques have been expanded to involve stakeholder segmentation, lifecycle concerns and scenario planning. These components are often missing fromlie cycle existing studies. Researchers can build on this method by adding digital tools like life cycle assessments, blockchain and AI-driven forecasts. All of these enhance the quality and effectiveness of decision-making. The method can be used for larger or smaller systems and different sectors. It is not limited to EV batteries; it can also be utilized to assess sustainability in complicated systems like hydrogen SCs and solar panel systems. Ultimately, this work contributes to theoretical progress in the field of sustainable SC management by showing that the expert inputs and involving multiple stakeholders helps in making better long term plans and improves the accuracy along with success of execution even in complex and uncertain conditions like market shifts, resource shortages and policy changes.

This method is suitable for researchers from different disciplines. It helps solve practical sustainability problems such as lifecycle management, green SC optimization as well as policy effect assessments. The model assists in making decisions based on evidence. It takes qualitative opinions from the stakeholder (such as interviews and surveys) and turns them into ranked priorities that can be acted upon. This helps connect academic theory with real-world applications. Researchers are working on evaluating public policies, assessing whether technologies are practically viable and planning sustainable strategies for specific regions. This makes it practical for consulting projects, collaborative work with industry and government or donor funded research. Especially when these projects require both accurate techniques and input from stakeholders.

5.3. Research limitations and future directions

While this study provides valuable insights, it is not without limitations. First, the scope is geographically confined to the Indian EV battery ecosystem. This enhances its practical significance for national policymakers and industry actors, but it also constrains the applicability of findings to other emerging economies or global contexts where supply chain structures, regulatory frameworks, and stakeholder behaviors may differ considerably. Future comparative research across regions would help identify both generalizable patterns and context-specific challenges.

Second, the analysis draws on the structured judgments of a panel of 15 experts. The number was chosen to balance stakeholder coverage with the cognitive demands of fuzzy pairwise comparisons and is consistent with established practice in fuzzy MCDM studies. To strengthen reliability, the design incorporated stakeholder-specific elicitation and aggregation, a shared fuzzy scale with geometric-mean aggregation, and consistency checks ($CR \leq 0.10$). Even so, reliance on expert opinion means that the results represent analytic rather than statistical inference. Future research could validate the findings with larger or cross-regional expert panels and complement them with quantitative approaches such as life cycle assessment (LCA), agent-based simulation, or big data analytics to enhance objectivity.

Third, while the expert panel captured diverse stakeholder categories, certain actors remain underrepresented, particularly informal sector recyclers and end-users who play critical roles in emerging economies. Their exclusion may limit the inclusiveness of the framework. Future studies should integrate these viewpoints to more

accurately capture ground realities and guide equitable policy formulation. Additionally, the present research does not examine interdependence or causal pathways among the identified criteria. Techniques such as social network analysis or structural equation modeling could be employed to explore cross-factor relationships and reliability among stakeholder roles.

Finally, the priorities identified here are temporally bounded, as EV battery technologies, policy regimes, and raw material markets are evolving rapidly. Replication of this framework at regular intervals and across different geographies would therefore be valuable to track shifting sustainability priorities and ensure the ongoing relevance of strategic decisions.

6. Conclusion

This paper presents a systematic, stakeholder-focused approach for identifying, assessing, and prioritizing obstacles and associated solution strategies to attain a sustainable and circular EV battery SC in India. The analysis employs a hybrid FAHP–FTOPSIS method guided by ST and Sustainability Theory, uncovering a complex network of interconnected priorities, contextual ambiguities, and strategic routes toward circularity.

Ten primary challenges, 35 subordinate challenges, and 14 solution strategies were assessed across six stakeholder categories: mining and resource extraction, raw material procurement, manufacturing and product development, SC and logistics, product management and strategy, and R&D. The mining sector highlighted environmental resource and lifecycle (ERL) issues, procurement and logistics players focused on supply network resilience (SNR), while upstream actors emphasized governance and regulatory alignment (GRA) as the most essential challenges. R&D stakeholders prioritized technology scalability and infrastructure (TSI), specifically TSI 1 (standardized innovation platforms), while digital integration for transparency (DIT) and research gaps and knowledge deficiencies (RGD) received comparatively little emphasis.

The FTOPSIS research indicated S12 (regulatory frameworks and safety compliance), S 11 (policy framework and compliance), S 10 (collaborative and stakeholder engagement), and S1 (resource efficiency and optimization) as the most influential solutions among stakeholder groups. Scenario-based sensitivity analysis illustrated the alteration of stakeholder priorities across multiple future scenarios. In a technology- and innovation-centric context, solutions such as S5 (battery design innovation), S 11, and S14 (material advancements) were favored. In a scenario dependent on imports, strategies prioritizing resilience and circularity, specifically S6 (circular economy focus), S9 (market incentives), and S 10, gained significance. These fluctuations highlight the necessity of adaptive policy planning that responds to both favorable and unfavorable conditions.

The present study enhances the current knowledge base by presenting the inaugural stakeholder-specific, uncertainty-informed prioritizing model within the context of the Indian EV battery CSC. This study tackles a significant gap in literature: the absence of integrated, multi-criteria decision-making frameworks that encompass both stakeholder diversity and scenario foresight. This study combines multi-stakeholder viewpoints with a dual-stage decision framework under uncertainty, contrasting with other research that regards sustainability in EV SCs solely as a technical or policy issue. This enhances the methodological application of FAHP–FTOPSIS within a complex, region-specific context and incorporates scenario foresight to improve long-term applicability.

Essential insights encompass, firstly, the affirmation that sustainability priorities are contingent upon stakeholders; secondly, a uniform cross-stakeholder focus on regulatory transparency and resource efficiency; and third, the significance of adaptable methods to address changing external challenges. The suggested framework offers a versatile method for facilitating policy and managerial decisions in evolving sustainability contexts.

7. Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the author(s) used QuillBot Premium for grammar correction, sentence refinement, and English editing. Following the use of this tool, the author(s) carefully reviewed, revised, and approved the final content, and take full responsibility for the accuracy and integrity of the published work.

CRediT authorship contribution statement

V.M. Aishwarya: Writing – original draft, Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Banu Yetkin Ekren:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Tej Singh:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis. **Vedant Singh:** Writing – review & editing, Visualization, Supervision, Software, Resources, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clscn.2025.100272.

Data availability

Data will be made available on request.

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