

Integrating sustainability across the lifecycle of electric vehicle batteries: Circular supply chain challenges, innovations, and global policy impacts

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Abstract

This study investigates the integration of sustainability practices into the circular supply chain (SC) of electric vehicle (EV) batteries to address environmental and economic challenges. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, a systematic review of 147 articles (2009–2024) identifies key challenges, solutions, innovations, and policy measures shaping the EV battery SC. The research uncovers 10 major challenges, 31 sub-challenges, and 160 detailed challenges, highlighting issues related to SC resilience, environmental impact, and economic sustainability. In response, 40 main solutions and 174 complete solutions are mapped, leading to the identification of 102 detailed technologies, 24 sub-technologies, and 8 core technologies supporting circular economy principles. These technologies are analysed for their long-term industry impact, with comparisons within categories to highlight their advantages, disadvantages, and contributions to circular economy goals. Additionally, global policy analysis reveals regulatory advancements, with China and the UK leading efforts to improve recycling, material recovery, and sustainability governance. This study also compares EV battery policies across countries using indicators like policy coverage, enforcement intensity, and effectiveness, highlighting their impact on sustainability and resource efficiency. A conceptual framework is developed to integrate these challenges, solutions, and innovations into a sustainable EV battery SC. The study concludes with theoretical insights, industry recommendations, and policy implications, offering a structured pathway toward sustainable and resilient EV battery SCs.

Highlights

- PRISMA review of 147 studies identified 160 EV battery circular supply chain challenges

- 174 solutions were mapped to address recycling, impact, and policy misalignment
- 102 innovations were found, including AI, blockchain, and cathode recycling
- China and UK led in EVB policy; gaps in EPR and global regulation remained
- An integrated sustainable circular supply chain model was proposed

Keywords: *Battery supply chain; circular economy; electric vehicle; supply chain resilience; recycling and remanufacturing*

Abbreviation	
GHG	Greenhouse gas
EVs	Electric vehicles
EOL	End-of-life
SCs	Supply chain
CE	Circular economy
SCSC	Sustainable circular supply chain
LIBs	Lithium-ion batteries
IoT	Internet of things
RQ	Research question
SLR	Systematic literature review
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
EESG	Environmental, economic, social, and governance
EPR	Extended producer's responsibility
R&D	Research and development
LCA	Life cycle assessment
EU	European Union
UK	United Kingdom
US	United States
DRC	Democratic Republic of Congo

1. Introduction

The transportation sector is a significant contributor to greenhouse gas (GHG) emissions and air pollution, with carbon emissions rising by over 250 million metric tons to approximately 8 gigatons in 2022, an increase of more than 3% compared to 2021[1]. To reduce this emission the development of electric vehicles (EVs) has become prominent solution to decarbonize transportation [1]. Transition to EV offers a significant option to minimize emissions which has the potential to reduce GHG emissions by up to 50% compared to conventional vehicles. On a wider view, EV adoption can cause to substantial reductions in future carbon emissions, contributing to global climate goals [2]. The global EV market is experiencing a rapid growth from \$ 538.8 billion in 2022 to \$ 906.7 billion by 2028 [3]. This surge in EV sales also fuels a growing demand for batteries, continuing the upward trend seen in recent years [3]. For instance, the demand of EV batteries has exceeded 40% of growth

compared to 2022 [4]. EV batteries are crucial not only for providing power to EVs but also for their function within a complex SC that begins with mining of critical components like that of lithium, nickel and cobalt [5].

These elements are processed and purified to produce the core components of EV batteries, driving both the upstream SC and the downstream recycling efforts needed to recover and reuse these critical materials [6]. Recycling batteries is vital for recovering these valuable materials, ensuring long-term sustainability, and minimizing environmental harm [7]. However, several challenges arise throughout the lifecycle of batteries, from manufacturing and utilization to disposal. Effective management is needed across all stages from material supply to end-user delivery and eventually to recycling. According to the International Energy Agency [8], the EV battery SC involves a network of entities responsible for the production and distribution of battery components and products expanding from mineral extraction to battery manufacturing, distribution and end-of-life (EOL) management. This complex system is marked by environmentally harmful practices, energy-intensive processes, and significant challenges associated with battery recycling [9]. Economic factors, such as SC vulnerabilities and fluctuating mineral prices, further exacerbate these issues [10]. Tackling these issues needs a comprehensive and sustainable approaches that focuses on responsible material sourcing, reducing waste and emissions, and incorporating advanced recycling and recovery technologies to ensure long-term sustainability factors [11].

Shifting towards a better sustainable framework, circular economy (CE) has progressed from classic 3Rs-reduce, reuse and recycle to include repairing, refurbishing and reproducing which provides a strong pathway for development [12]. By integrating CE principles, comprehensive and sustainable solutions can be developed to address sustainable challenges, focusing on managing responsible material sourcing, reducing waste and emissions, and incorporating advanced recycling and recovery technologies to ensure long-term environmental, economic, and social sustainability [13]. This approach not only extends battery life through the recovery of valuable materials for reuse but also optimizes design and maintenance along with improving the manufacturing process of EV battery components [14].

Eventually, these initiatives can notably minimize the carbon footprints of the EV sector, promoting latest economic prospect along with maximizing social and governance results by encouraging responsible practices and fair growth within the industry [15]. Figure 1 depicts the EV battery SC process within a CE, emphasizing the cycle from raw material extraction to recycling. After this conceptual introduction, it is necessary to comprehend the details of the EV battery SC. The SC of EV batteries, situated within the larger framework of

sustainable practices, involves a series of intricate, energy-intensive procedures essential for the EV industry [16]. The extraction of vital raw materials, such as lithium from ores or brine, is followed by their refinement by advanced techniques, such as air floatation, smelting, and chemical leaching, to yield high-purity compounds like lithium carbonate or hydroxide [17]. These molecules are subsequently transformed into essential battery components and combined into cells, modules, and packs [18]. This comprehensive exploration of the encompasses the installation of battery packs in and their subsequent delivery to consumers [19]. Upon reaching the end of their lifespan, EV batteries are subjected to sophisticated recycling methods to extract and refine valuable elements, which are then reintegrated into the manufacturing process, so completing the circular lifecycle of these materials [20].

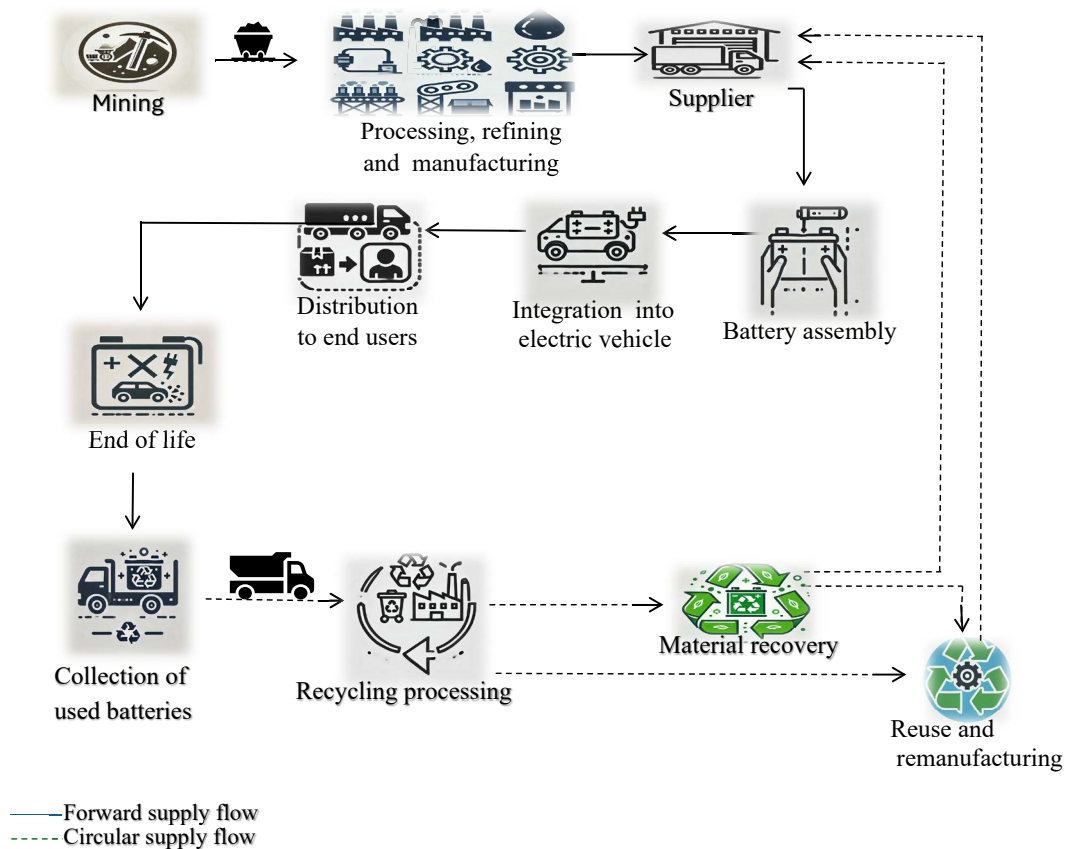


Fig. 1. Process flow diagram for EV battery supply chain.

The existing literature has thoroughly examined the sustainability concerns in the EV battery SC, highlighting critical issues such as resource shortages, ineffective recycling methods, and regulatory deficiencies. For example, studies like Ramasubramanian et al. [21] recognized substantial sustainability difficulties in lithium-ion batteries (LIBs) production chain and determined that the incorporation of sustainable technology and enhancement of

labour practices are crucial for its progress. But failed to offer a comprehensive global policy perspective and to investigate a larger spectrum of innovative technologies and CE practices. Niri et al. [22] conducted a comprehensive analysis on sustainability concerns related to EV batteries, emphasizing the importance of technological environmental consequences, resource scarcity, and socio-economic variables within the EV battery SC. Their findings emphasize environmental consequences, resource constraints, and the socio-economic factors associated with the EV battery lifecycle. Moreover, certain studies concentrate on certain domains such as recycling technology or policy effects and their methodological implementation. For instance, studies like Hantanasirisakul and Sawangphruk [23] assessed current recycling technologies and their immediate environmental and economic impacts but do not explore the long-term effects or the global integration of these technologies. Picatoste et al. [24] emphasized the variability in environmental impact due to different methodological approaches and key points of concern. Rajaeifar et al. [25] examined lifecycle issues that pose political and economic risks throughout the lifespan of LIBs. Even so, these literatures collectively failed to provide a thorough analysis of the entire sustainability framework.

To tackle these limitations, this study proposed research question (RQ) as follows: RQ: In what ways do technological advancement and policy measures tackle the challenges and enhance the sustainability of the EV battery SC?

To address the RQ, we set four specific objectives as: i) to identify challenges and solutions; ii) to evaluate technological innovations; iii) to evaluate global policy frameworks regarding their effects on the sustainability of the EV battery SC; iv) to establish a conceptual framework that synthesizes challenges, solutions, technological innovations, and global policy.

1.1. Novelty and contributions

This study introduces a comprehensive literature evaluation, aimed at synthesizing and integrating information from various sources. It enables a thorough assessment of sustainability practices across several regulatory frameworks and technological contexts within the EV battery SC. This paradigm distinctively integrates insights from existing research on advanced recycling technology, policy analysis, and CE concepts, in contrast to previous studies. The paper provides a comprehensive integration of these factors, addressing significant gaps in the literature and giving practical solutions to issues such as resource management inefficiencies, recycling constraints, and regulatory discrepancies. This integrative approach offers novel insights that enhance both scholarly comprehension and practical implementation, especially

by emphasizing avenues for strengthening SC resilience and sustainability. The study establishes contributions based on these objectives. It first identifies difficulties and solutions by synthesizing and mapping critical concerns in resource management inefficiencies, recycling obstacles, and regulatory deficiencies within the EV battery SC (objective 1). This understanding improves SC resilience by providing stakeholders with a thorough understanding of essential challenges and possible solutions for mitigating them. Secondly, the study assesses technological developments by examining their applications, long term industrial impacts, and comparative efficacy within each category (objective 2). This offers stakeholders critical insights into technological changes and their correspondence with long-term sustainability goals. Third, the study compares global policy frameworks' influence on EV battery SC sustainability (Objective 3). The study suggests ways to improve regulatory frameworks, promote CE concepts, and link policies with global sustainability goals by identifying regulatory gaps and inconsistencies. These insights give policymakers and industry executives real solutions to regulatory issues and resilience in environmental, economic, and social areas. Finally, the study develops a conceptual framework, incorporating challenges, solutions, technical advances, and policy consequences (Objective 4). This approach gives stakeholders a holistic view of the EV battery SC and practical advice for sustainability and resilience. The framework helps industry executives and policymakers improve SC sustainability and meet global sustainability goals by addressing significant gaps.

This study advances academic knowledge and provides practical applications for stakeholders to maintain the sustainability and resilience of the EV battery SC. This unified strategy is crucial for meeting future demands as the global shift to EVs progresses rapidly. Moreover, the amalgamation of difficulties, technical advancements, and policy implications into a cohesive framework establishes a basis for future research and support global initiatives aimed at sustainable development.

The paper is structured as follows: Section 2 outlines the methodology used in the systematic review. Section 3 presents the dual results from the review, including both descriptive and thematic findings. Section 4 discusses the integration of sustainability with circular SC practices. Section 5 explores the implications and policy recommendation of the study. Finally, Section 6 addresses the conclusion, limitations, and potential directions for future research.

2. Methodology: Systematic literature review

This research employs a Systematic literature review (SLR) approach, recognized, for its rigor and transparency. SLR involves a comprehensive search of the literature, followed by an in-depth evaluation and synthesis of findings [26]. This process helps researchers stay current with the latest evidence and underline areas that may require further investigation. It ensures that assessments are comprehensive, unbiased, and replicable, thereby aiding evidence-based decision-making [22]. We design a review process following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, which enhances the transparency and rigor of the review. Figure 2 provides a detailed flow diagram outlining the methodological approach employed in this study.

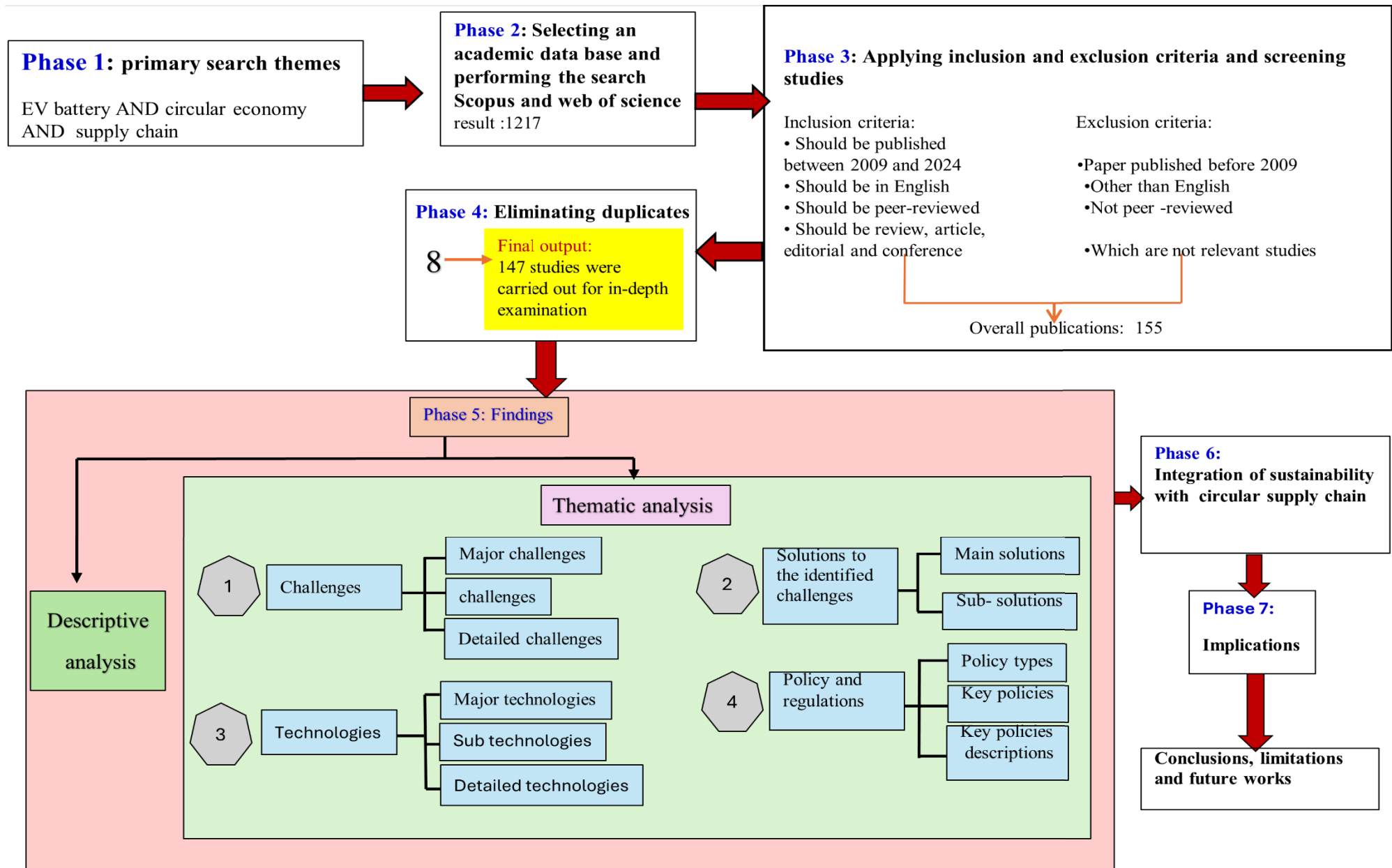


Fig. 2. Detailed flow diagram of the conducted SLR.

According to that, the research begins by defining the primary search themes, which focus on "EV battery," "circular economy," and "supply chain." These themes, along with selected sub-keywords detailed in Table 1, are used to generate the search string. This search string is then applied in the Scopus and Web of Science databases during the second phase, yielding an initial pool of 1,217 publications. In the third phase, the 8 duplicates are removed. In the fourth phase, the retrieved articles are subjected to a rigorous screening process based on clearly defined inclusion and exclusion criteria. These criteria ensure that the selected studies are relevant, peer-reviewed, published between 2009 and 2024, and written in English. After applying these filters, the number of relevant publications is narrowed down to 147.

The fifth phase focuses on conducting both descriptive and thematic analyses of these studies. The thematic analysis is organized into four key areas: challenges in the EV battery SC, potential solutions, innovative technologies, and relevant policy and regulatory frameworks. Each of these areas is explored in detail, with the analysis identifying major and sub-challenges, evaluating solutions and technologies, and reviewing policies that impact sustainability in the SC. In the sixth phase, the insights from these analyses are synthesized to explore how sustainability can be integrated with circular SC practices in the EV battery industry. This phase is crucial for the goal of this study, for understanding the role of CE principles in enhancing sustainability and mitigating environmental impacts. Finally, the seventh phase discusses the broader implications of the findings, providing conclusions, highlighting the limitations of the study, and suggesting directions for future research. This structured approach ensures a comprehensive understanding of the challenges, solutions, and innovations needed to improve the sustainability of the EV battery SC. The next section delves into the descriptive analysis of the 147 selected articles.

Table 1
Keyword sets.

Supply chain	Circular economy	Electric vehicle battery
Sustainable supply chain	Circular economy principles	Battery life cycle
Reverse logistics	Material circularity	Battery recycling
Value chain	Reuse	Lithium-ion batteries
Closed loop supply chain	Recycling and upcycling	Battery technologies
Material flow analysis	Waste reduction	Battery reuse
End-of-life management	Life cycle assessment	Battery performance

3. Dual analysis

This section offers a dual perspective analysis crucial for comprehending the scope and intricacies of sustainable circular SCs for EV batteries. The analysis commences with a descriptive examination that establishes the foundation by elucidating the quantitative and qualitative data gathered from multiple investigations. Building on this base, the thematic analysis explores a more profound interpretation of the data, emphasizing critical topics concerning difficulties, solutions, innovative technology, and international rules and regulations. These topics are derived from a SLR, providing insights into prevailing trends and patterns that impact the strategic advancement of SCSC for EV batteries.

3.1. Descriptive analysis

This section presents a descriptive analysis of the study's findings on SCSC of EV batteries by providing an overview of the existing trends and patterns identified from literature.

Figure 3(a) shows the evolution of publications from 2009 to May 2024 in the field. It reveals that only one article was published in 2012, with growth becoming steady from 2018 onwards, although not entirely regular. There is a noticeable dip to 9 publications in 2020, likely due to disruptions caused by the COVID-19 pandemic. However, publication numbers rebounded, rising from 10 in 2021 to 31 by 2023, and as of May 2024, there are already 29 publications. This highlights a significant peak in research activity over the last 15 years, with the last five being particularly active. This increase may be attributed to the growing global focus on sustainability and the rising importance of addressing climate change through innovations in EV battery SCs.

Figure 3(b) indicates the top 14 journal-wise publication analysis. Resources, Conservation, and Recycling published the utmost research papers on this topic, followed by the Journal of Cleaner Production with 10 publications, and Renewable and Sustainable Energy Reviews with 9 publications are top three journals. These details may provide directions for researchers to determine which journals can likely publish their research study.

Figure 3(c) shows the author-wise publicization. Heidrich O has the most publications with seven articles, followed by Li Y and Rajaeifar, each with five articles emphasizing the collaborative nature of this SCSC field.

Figure 3(d) displays top 14 countries with highest number of publication papers. China has 48 publications, being the leading countries in the publication. This could be due to its broad EV market, strong government support and outstanding manufacturing existence.

Besides, the United States, United Kingdom, and Germany has 36, 29, and 17 publications, respectively. This research magnifies SCSC for EV batteries by encouraging interdisciplinary collaborations, informing policy and driving global and sustainable innovation in industry.

Figure 3(e) depicts a bibliographic co-occurrence map, generated using VOS viewer, visualizing the relationships between key terms in the field. The size of each node represents the frequency with which the corresponding term appears in the literature, while the connections between nodes indicate co-occurrence or relatedness in the research. According to that, the most prominent terms, such as "lithium-ion batteries," "recycling," "electric vehicles," and "sustainable development," highlight the central focus areas in this research field. "Lithium-ion batteries" and "recycling" are closely linked, indicating a strong emphasis on the lifecycle management and material recovery of batteries. Terms like "environmental impact," "electronic waste," and "supply chain management" suggest growing concerns around waste management and the sustainability of the entire battery SC.

Different colours represent clusters of related topics. For instance, "electric vehicles" and "sustainable development" form one key cluster, while "recycling" and "electronic waste" represent another, showing how interconnected these research areas are. Topics such as "life cycle assessment," "energy storage," and "lithium" also appear frequently, emphasizing the technical and environmental challenges faced in battery production and end-of-life management. The interconnectedness of terms like "greenhouse gases," "climate change," and "battery production" illustrates the broader environmental and policy discussions surrounding the EV battery industry, while more specific terms such as "nickel," "cobalt," and "material flow analysis" point to the growing interest in SC efficiency and the critical materials involved in battery production. The findings from the descriptive analysis highlight a significant and growing interest in the SCSC of EV batteries over the past 15 years, with a marked increase in publications, particularly in recent years. Additionally, the keyword analysis underscores the importance of topics like "lithium-ion batteries," "recycling," and "sustainable development," indicating these are central themes driving research in the SCSC of EV batteries.

The next section delves into the analysis of the selected articles, focusing on the emerging themes identified within the literature.

3.2. Thematic analysis

This section categorizes the themes from challenges and solutions, innovative technologies, and global policy and regulations perspectives identified from the SLR.

3.2.1. Challenges and solutions

This section addresses Objective 1 aiming to provide a comprehensive understanding of the challenges hindering the CE of EV battery. In line with this objective, ten major challenges have been identified, which are further divided into 31 sub-challenges and 160 detailed challenges (refer to Appendix A for a complete list). These findings are summarized in Table 2 and visually represented in Figure 4, offering a clear overview of the multifaceted obstacles that must be overcome to advance the CE of EV battery. For example, from Figure 4 it is observed that, within the broader challenge of “environmental impact and sustainability”, the first sub-challenge identified is resource scarcity, management, and extraction. This sub-challenge is broken down into detailed challenges labelled as resource scarcity and environmental degradation (RSME1), limited global lithium storage (RSME2), scarcity and cost management for critical resources (RSME3), sustainable resource management challenges (RSME4), ethical issues in resource extraction (RSME5), introduction of heavy metals into ecosystems (RSME6), geopolitical risks in lithium supply security (RSME7). The second sub-challenge focuses on production and manufacturing, with corresponding detailed challenges labelled PM1 through PM5 and so on (see Appendix A). These sub-challenges and their associated detailed challenges provide a thorough breakdown of the specific issues that must be addressed to overcome the environmental and sustainability hurdles in the CE of EV batteries.

Table 2 highlights that SC and economic resilience emerge as the most significant challenges, identified by 67% of the studies. This underscores the critical need for robust and adaptable SC capable of withstanding disruptions. Environmental impact and sustainability are the next most frequently cited challenges, noted by 57% of the studies. Recycling and material management are also significant, mentioned in 32% of the articles. Technological innovation and infrastructure, along with policy and regulatory frameworks, are prominently featured as challenges in 36% and 26% of the studies, respectively.

Table 2**Paper-based challenges in establishing a SCSC for EV batteries.**

Major challenges	Authors/ year	No. of study (%)
1) Environmental impact and sustainability	[11], [21-24], [25], [28-109]	57%
2) SC and economic resilience	[11],[21], [22], [25], [28], [36-38], [43], [49], [52-56], [58], [59], [62], [63], [65-68], [70], [73-81], [83-85], [88], [91-94], [96-98], [100], [102], [104], [106-154]	67%
3) Recycling and material management	[21-23], [29-31], [40], [50-53], [55], [65], [70], [71], [74], [76], [77], [79], [80], [9], [82], [83], [85], [87], [88], [91], [92], [94], [96], [98], [136], [137], [139], [142], [144], [148], [150], [153-159]	32%
4) Technological innovation and infrastructure	[11],[21], [42], [51], [61-63], [65-67], [69], [71], [72], [74], [76], [77], [79], [80], [84-87], [89], [91-94], [96], [97], [107], [112], [115], [117], [130], [138], [144], [146], [147], [149], [150], [154], [157], [158], [159-166]	36%
5) Policy and regulatory framework	[22], [33], [38], [39], [42], [50], [51], [61-63], [70], [71], [72], [78], [84], [85], [90], [93], [94], [97], [100], [107], [127], [130], [136], [137], [140], [144-146], [154], [164], [167], [168]	26%
6) Resource-efficiency and alternative materials	[22], [45], [60-62], [68], [80], [84], [85], [87], [91], [96], [97], [143], [148], [158], [159]	12%
7) Digital transformation for sustainability	[57], [79], [114], [129], [152], [154], [161], [164]	5%
8) Research and systematic analysis	[45], [57], [72], [19], [74], [91], [96], [142], [144], [149], [150], [164], [165], [167]	10%
9) Social and legal implications	[21], [22],[58], [64], [68],[78],[82],[84],[93],[96], [98], [122], [123], [147], [152]	10%
10) Industrial process efficiency	[28], [50], [79], [81], [84], [85], [87], [88], [89], [90], [91], [96], [99], [104],[105], [117], [129], [139], [148], [149], [150], [168]	14%



Fig. 4. Comprehensive classification of challenges in establishing SCSC of EV battery (Note: For detailed challenges see Appendix A).

Figure 5 addresses a comprehensive classification of solutions developed in response to the challenges outlined in Table 2. The study identifies 40 main solution and 174 detailed solutions to the challenges (see Appendix B for the details). The Figure 5 represents scattering of the literatures pointing on solutions to these challenges. Precisely, solutions addressing the challenges of environmental impact and sustainability are studied in 53% of the articles. While 51% of the papers focus on addressing innovative technology and infrastructure. Solutions for recycling and material management challenges are covered by 47% of the articles, and SC and economic resilience is addressed by 41% of papers. Policy and regulatory framework solutions is discussed in 37% of the papers, resource-efficiency and alternative materials is presented in 33% of the literatures along with industrial process efficiency 35% of the papers. Research and systematic analysis are addressed by 25% of the papers, digital transformation for sustainability mentioned by 22% of the articles as well as 17 % of the articles addresses social and legal implications. In the following section, we delve into each of these challenges and their respective solutions by discussing relevant articles and their findings. This shows a deep understanding on how current research tackle different challenges in the EV battery SC.

In the following sub-sections, we explore each of the ten challenges identified in Table 2 in detail.

3.2.1.1. Environmental impact and sustainability

Every stage of the SC that is from resource extraction to EOL disposal distinct challenges, so achieving an overall sustainability in SC is complex [22]. Environmental impact and sustainability challenges primarily focus on addressing resource scarcity and minimizing the environmental degradation linked to battery production and resource extraction. These challenges are divided into four sub-categories and 29 detailed challenges (see Appendix A), and they are discussed in 57% of the reviewed articles. The sub-challenges include the impacts of resource extraction, production and manufacturing processes, recycling, disposal and waste management methods, and sustainability and impact assessment risks (see Table 2 and Figure 4). This challenge is the second most frequently covered in the literature, highlighting its critical importance.

Resource scarcity, management and extraction challenges involve the limited availability of critical minerals like lithium and cobalt, leading to increased mining activities that substantially exacerbate environmental degradation, including deforestation, water pollution, and habitat destruction [11, 88, 106]. The scarcity of these resources results in

unpredictable cost management and encourages unsustainable extraction practices, which introduce harmful heavy metals into ecosystems, cause biodiversity loss, and contaminate soil and water [24, 28, 29]. Ramasubramanian et al. [21] highlighted that resource depletion, environmental degradation, and ethical concerns in raw material extraction result in ongoing environmental contamination and resource constraints, which in turn affect the scalability of sustainable EV production. Das et al. [30] stressed that cobalt-intensive extraction methods substantially exacerbate marine and freshwater ecotoxicity due to pollution from ore mining and processing, with environmental repercussions intensifying as ore grades diminish. Moreover, the concentration of resource supplies in a limited number of nations raises SC vulnerabilities, hence raising the possibility of unexpected shortages that might destabilize the global EV generations [75, 82, 86]. In addition, complicating efforts to establish a sustainable SC are ethical issues which involve unsafe working conditions and displacements of local communities [31, 33, 43].

Another significant challenge is the high energy consumption and emissions related to battery manufacturing and production [42]. Since EV battery production mostly depends on fossil fuels, resulting in carbon dioxide emissions [46, 97]. The production process alone significantly adds to the overall carbon footprints of EVs, mostly due to high energy usage, material processing and waste generation [25, 92, 95]. Achieving the net zero emissions targets is getting more challenging given the increasing demand for battery materials [22,35]. Although the shift towards renewable energy sources is necessary for battery manufactures still it remain difficult due to infrastructure restrictions and high costs [22].

Additionally, significant obstacle to sustainability is recycling practices and waste management inefficiencies [62, 103]. Mrozik et al. [38] emphasized that inadequate disposal and degradation of spent LIB led to substantial contamination of soil, water, and air via leaching, material degradation, and the emission of hazardous compounds, hence intensifying environmental hazards. Existing recycling methods are insufficiently efficient to reclaim all valuable materials, resulting in resource depletion and prolonged environmental contamination [56]. Existing recycling methods are insufficiently efficient to reclaim all valuable materials, resulting in resource depletion and prolonged environmental contamination [81, 91]. The management of hazardous chemicals in recycling presents safety hazards, and the diversity of battery chemistries challenges the advancement of efficient recycling methods [61,76, 80]. The absence of standardized battery chemistry complicates recycling initiatives even more since different battery compositions require for different recovery techniques, thereby lowering the

general efficiency of existing recycling methods [61]. The management of hazardous chemicals in recycling presents safety hazards for works and requires safety rules [76, 80].

Sustainability and impact assessment is the evaluation of the environmental ramifications of battery technologies, a process that is essential yet intricate [62, 63, 66]. The absence of established metrics for assessing sustainability and the challenges in executing environmentally friendly actions during the battery's lifecycle are significant obstacles [51-53]. The environmental impact of EV is significantly influenced by the regional energy generating mix, which varies considerably, hence impacting the overall sustainability of EV [27, 88, 105].

Addressing the environmental impact and sustainability challenge is vital, as it aims to minimize the negative environmental effects identified throughout the SC stages of EV batteries. To tackle these challenges, 18 comprehensive solutions have been identified and divided into four sub-solution categories (see detailed in Appendix B). Figure 5 shows that these solutions are discussed in 53% of the articles and include strategies such as implementing resource efficiency and circular practices, leveraging technological solutions for sustainability, enforcing strict policy guidelines to minimize environmental impact, and enhancing sustainability in manufacturing and energy resource use. Improving sustainability in the EV battery SC requires short-term alternatives that focuses on CE methods, bettering recycling techniques, policy enforcement strengthening, and support of sustainable manufacturing practices [34, 54]. While EOL optimization guarantees effective disposal and recovery of spent batteries, increasing reuse, remanufacturing, and recycling can greatly lower dependency on virgin materials [29]. Improvements in recycling such as safer handling of hazardous materials [38, 56] and optimal mechanical and hydrometallurgical recycling techniques may raise the recovery rates of nickel, cobalt, and lithium among other important metals [25, 55]. Strict environmental rules [76] and required take-back programs help to strengthen policy enforcement and hence support appropriate battery waste management [61, 76]. Furthermore, assisting to lower emissions and dependency on newly mined resources are low-carbon production techniques [69, 70] and promoting the use of recycled and secondary raw materials in industry [73].

Long-term solutions need for global cooperation, artificial intelligence-driven sustainability evaluations, structural improvements in energy integration and battery technologies [77], while the development of alternative materials such silicon anodes and sulphur-based cathodes improves sustainability, investing in solid-state and sodium-ion battery chemistries can help to lessen dependency on rare resources such lithium and cobalt [80]. Changing battery manufacture to renewable energy sources like solar and wind and supporting green energy

policies can help the sector's carbon footprint to be reduced [122]. Standardized life cycle assessment (LCA) approaches and multi-objective optimization models driven by artificial intelligence can help battery design and manufacturing to better estimate sustainability measures [29]. At last, encouraging worldwide legislative frameworks and international alliances for ethical raw material procurement would help to minimize SC interruptions and guarantee a more robust, sustainable battery sector [120,127]. By emphasizing the environmental impact and sustainability challenges, and proposing targeted solutions, the findings can lead to focused interventions in the SCSC.

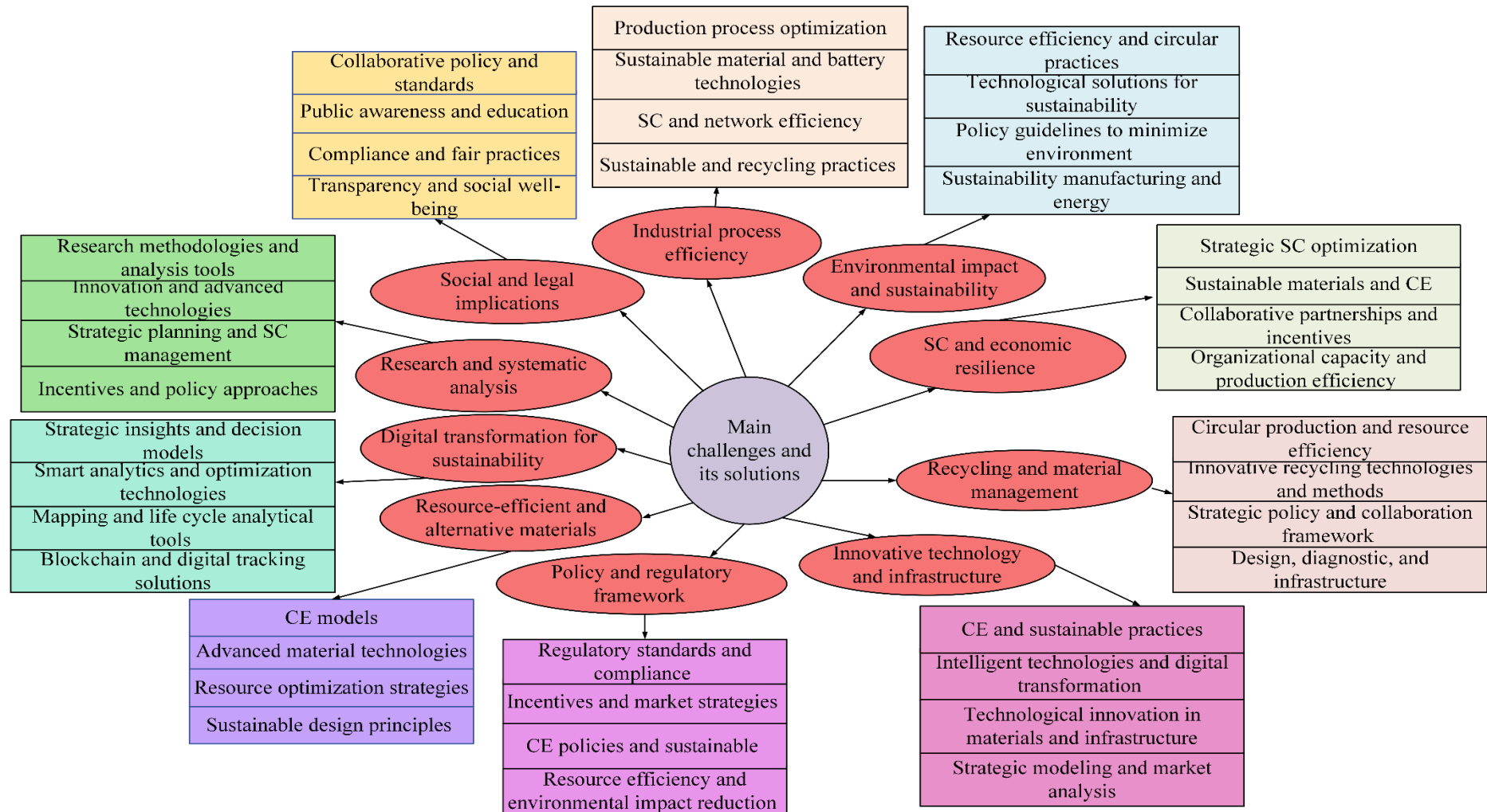


Fig. 5. Comprehensive classification of solutions addressing challenges (Note: For sub solutions see Appendix B).

3.2.1.2. Supply chain and economic resilience

The SC and economic resilience concerning EV batteries involves a complex framework characterized by critical vulnerabilities and dependencies that directly affect the strength and dependability of the SC [32]. This sector is notably impacted by difficulties in obtaining a stable supply of essential commodities, exacerbated by geopolitical concerns, price fluctuations along with concentrated distribution systems [75]. SC and economic resilience barriers encompass four sub-challenges and 27 detailed challenges (as outlined in Appendix A), with 67% of the reviewed articles addressing these issues, as summarized in Table 2. This challenge is recognized as the most significant, with the highest percentage of attention in the literature. It encompasses risks related to SC structure and security, material and resource skills, economic resilience and market dynamics, as well as technological and operational efficiency (see Table 2 and Figure 4). The main concern in SC is the structural and security issues regarding the concentration of vital components such as lithium, cobalt, and nickel in specific geographic areas, as this increases the possibility of supply interruptions [112, 121, 128]. Villa-Mendoza et al. [65] revealed that political unrest, trade restrictions, or natural calamities cause global SCs to bottleneck, which causes material shortages directly affecting the manufacturing of LIBs. The SC is especially sensitive to geopolitical conflicts and export restrictions because of its reliance on limited material sources, therefore complicating supply stability [31, 100, 145]. Moreover, inadequate recycling infrastructure reduces the circular supply of battery materials since current facilities cannot manage significant needs for battery recovery and processing [102, 140]. Lack of connectivity and integration among several SC stages aggravates material flow delays and disturbs SC coordination [104].

Regarding material and resource concerns, price volatility and changing supply availability seriously compromise SC resilience [88, 125]. Inconsistent pricing for raw materials, especially cobalt and lithium, which are prone to market speculation and geopolitical tensions [83, 84], compromises the economic viability of battery manufacture. Since demand for battery-grade materials exceeds supply capacity [134, 135], long-term resource shortages pose even more of a threat to production stability [107-109]. Key issues also include market dynamics and economic resilience since capital-intensive recycling activities affect financial planning [92, 94, 110], and unpredictable market demand for second-life batteries influences these aspects as well [113-115]. The economic feasibility of EV battery SC operations is quite susceptible to changes in government incentives, trade regulations, and worldwide demand [73,

97, 136]. Finally, SC resilience is largely influenced by operational and technological efficiency [132]. Manufacturers and recyclers bear financial loads from the high cost of recycling techniques and ineffective material recovery systems [118, 130].

Another challenge is technological obsolescence since recycling systems cannot match changing battery chemistries, therefore restricting recovery efficiency [37, 39, 133]. Furthermore, taxing SC operations and raising manufacturing costs are logistical inefficiencies like poor infrastructure for processing old EV batteries [116, 117]. Manufacturers also battle to balance cost control with production scalability, which results in ineffective inventory control and material distribution [102, 111, 127].

To address these issues, 41% of the reviewed literature proposes solutions. Two sub-solutions and twelve detailed solutions (outlined in Appendix B) are implemented to mitigate these challenges. Figure 5 shows the proposed incentives and stabilizing the SC in through strategic optimization, promoting sustainable materials and CE practices, fostering collaborative partnerships and incentives, and enhancing organizational capacity and production efficiency. These solutions are crucial for strengthening the resilience and sustainability of the EV battery SC. In the immediate future, enhancing strategic SC optimization is crucial for minimizing inefficiencies, alleviating supply disruptions, and augmenting operational coordination [119]. Centralized decision-making and improved logistics management using advanced analytics can reduce transit delays and bottlenecks, enabling efficient material flow and the timely delivery of vital raw materials [138, 142]. Moreover, diversifying supply sources mitigates reliance on geopolitically unstable areas, safeguarding against market volatility and abrupt material scarcities [53, 165]. Augmenting resource recovery rates by improved recycling programs offers a sustainable method for diminishing dependence on virgin raw materials, especially lithium and cobalt [44, 46]. Companies must optimize production and inventory management to avert stock shortages and excessive dependence on external suppliers [132, 156]. Utilizing second-life battery applications in energy storage prolongs battery lifespan, stabilizes supply, and reduces waste [155, 160].

In the long term, promoting sustainable material utilization, enhancing CE initiatives, and bolstering SC resilience through infrastructure enhancements are essential [31]. Creating alternate battery chemistries that diminish reliance on limited resources like cobalt can alleviate raw material scarcities and price fluctuations [22, 148]. Advanced recycling methods that augment material recovery rates will facilitate the reintegration of additional lithium-ion battery components into the SC, mitigating environmental effect and promoting long-term

sustainability [46, 106]. Enhancing strategic alliances throughout the SC by increased collaboration among manufacturers, recyclers, and lawmakers will augment coordination and efficiency, resulting in a more robust SC adept at adjusting to market swings and supply interruptions [95, 156]. Yue et al. [108] highlighted that enhanced production configurations and streamlined inventory management facilitate material handling, guaranteeing the availability of essential inputs as required, while preventing surplus stock and production delays. Furthermore, optimizing facility locations and enhancing transportation networks will improve SC efficiency, alleviating logistical limitations and decreasing transportation expenses [112, 121, 124]. Through persistent investment in resource-efficient production and sustainable material procurement, organizations can develop a more adaptable, resilient, and competitive SC capable of enduring prolonged economic and market adversities [119, 161].

3.2.1.3. Recycling and material management

The recycling and material management challenge arise when attaining high recycling productivity and material effectiveness to recover the retired EV batteries [22, 154]. This barrier consists of three sub-challenges and sixteen detailed challenges (outlined in Appendix A), which are discussed in 32% of the reviewed articles. The key challenges stem from technological advancements and efficiency, resource management and recovery, framework and infrastructure, as well as economic and environmental factors which makes it critical to address these issues (See Table 2 and Figure 4). A major difficulty is the lack of a coherent recycling framework and insufficient infrastructure, resulting in fragmented recycling methods and inefficiencies [41]. Present recycling facilities are deficient in technological capabilities and capacity to manage the increasing amount of EOL batteries, hence limiting scalability and efficacy [40, 96]. The absence of established protocols for battery collecting, processing, and disposal hinders the widespread use of efficient recycling solutions [94]. Chen et al. [154] assert that although pyrometallurgy, hydrometallurgy, and direct recycling technologies are available, none are completely optimized, resulting in economic inefficiencies and suboptimal material recovery rates. The restricted access to innovative recycling technology hinders the industry's ability to efficiently recover materials and reintegrate them into the production cycle, thus heightening dependence on virgin raw materials [94, 136, 163].

Similarly, another major problem in battery recycling is the technological inefficiency in extracting useful elements from LIB [55, 70]. Sommerville et al. [87] discovered that contemporary recycling techniques predominantly emphasize the recovery of high-value

metals, including cobalt and nickel, leading to resource inefficiencies, limited closed-loop recycling, and increased expenses. The variety of battery chemistries and designs complicates the recycling process, necessitating specific knowledge, flexibility, and adaptation [71, 141]. Harper et al. [139] observed that the swift proliferation of EV usage has surpassed the development of scalable and economical recycling technologies, resulting in heightened material losses and operational inefficiencies. Kotak et al. [40] emphasized the difficulties in recycling EV batteries, mostly due to the intricacies of life-cycle analysis and the absence of a standardized approach, which constrains the scalability and sustainability of second-life applications.

The least significant yet still pertinent difficulty regards to the economic and environmental limitations in EV battery recycling [150]. Financial obstacles impede the economic feasibility of large-scale recycling owing to elevated operational expenses, insufficient economic incentives, and the challenges of incorporating recycling into current business frameworks [143]. Hantanasirisakul and Sawangphruk [23] asserted that economic inefficiencies in lithium-ion battery recycling led to financial instability, hindering investment in sustainable recycling solutions. The incorrect disposal of hazardous battery components, including lithium, cobalt, and electrolyte solutions, presents significant ecological and health hazards [23]. The high prices of green recycling technology compound these concerns, hindering industries' shift to sustainable recycling alternatives [150].

To improve recycling and material management, Figure 5 depicts four sub-solutions, and eighteen comprehensive approaches (see Appendix B), featured in 47% of the reviewed literature. These challenges can be mitigated by promoting circular production and resource efficiency, advancing recycling technologies, introducing strategic policy frameworks and collaborative efforts, and implementing design, diagnostic, and infrastructure improvements for more effective material recovery (see Figure 5). In the short term, enhancing SC and economic resilience in the EV battery sector necessitates the augmentation of operational efficiency and resource use via enhanced production and recycling methodologies [61-63]. Improving production techniques to eliminate energy waste and optimize material handling might alleviate pressure on current SC and decrease operational expenses [45, 49]. Improvements in CE strategies such as incorporating recycling and reuse from the design phase, facilitating the effective reintegration of recovered elements from end-of-life batteries into the manufacturing cycle, thus reducing reliance on virgin raw materials [51–53]. Simultaneously, the implementation of advanced recycling technologies that enhance recovery rates and material purity effectively alleviates supply disruptions and minimizes waste,

fostering a more resilient and economically sustainable SC [78, 81, 86]. The prompt interventions, such as optimized logistics and refined production processes, establish a foundation for a more stable SC by minimizing resource inefficiencies and augmenting overall material usage [40, 45].

In the long term, achieving SC resilience necessitates a strategy shift towards sustainable and integrated production [143]. Progressing technological innovations like the creation of battery designs featuring improved recyclability and modular configurations will substantially prolong battery lifespans and facilitate the reutilization of essential materials, thus alleviating geopolitical concerns and price fluctuations [99, 111, 148]. Creating a fully integrated CE via innovations in direct recycling methods and second-life battery applications will ensure a steady supply of recycled materials, diminishing dependence on new raw material extraction and mitigating overall environmental impact [147]. Moreover, cultivating cooperative partnerships among manufacturers, recyclers, and suppliers is crucial for enhancing material collection, distribution, and processing throughout the whole SC [140, 155]. Incremental strategic investments in infrastructure will facilitate the development of a robust and flexible SC [160]. Ongoing enhancements in production efficiency will augment overall sustainability [166, 167]. Improvements in resource recovery technology will enhance economic stability, allowing the SC to endure market volatility and prolonged resource difficulties [149, 153].

3.2.1.4. Technological innovation and infrastructure

Technological innovation and infrastructure challenge arises from ongoing issues related to advancing technology and developing the necessary infrastructure to support efficient battery lifecycle management [46]. Thirty-six percent of the reviewed papers address two sub-challenges, and 23 specific concerns related to technological innovation and infrastructure (see Table 2 and Figure 4). These challenges are categorized into battery recycling and disposal, as well as battery development and integration. The difficulty of battery recycling and disposal represents the most significant technological obstacle, since it directly affects material recovery, resource availability, and environmental sustainability [158]. The absence of regulated recycling procedures leads to variable material recovery rates and inefficiencies in the extraction of key metals, including lithium, cobalt, and nickel [71]. Present mechanical, pyrometallurgical, and hydrometallurgical recycling methods are expensive, energy-consuming, and environmentally detrimental, constraining their scalability and economic

feasibility [86]. The lack of adequately equipped recycling infrastructure results in inefficiencies in processing EOL EV batteries, causing resource wastage and heightened reliance on the extraction of basic raw materials [42, 129]. Considering these pressing issues, it is imperative to rectify the inefficiencies in battery recycling and disposal to attain a sustainable and robust EV battery SC while mitigating environmental damage and material shortages [164].

The battery development and integration problem pose considerable difficulties, albeit it is somewhat less pressing than other technological impediments [11, 149]. A primary concern is the absence of standardization in battery chemistries, which complicates manufacturing processes and restricts interoperability among EV models emphasized by Kwade et al. [117]. Manufacturers must regularly adjust to novel materials and production methods, resulting in elevated costs and inefficiencies [115, 154]. The lack of precise battery health monitoring and lifespan prediction models impedes second-life applications, limiting prospects for reuse in energy storage and other sectors [158, 166]. Accelerated progress in battery technology, although advantageous for performance, frequently surpasses the evolution of supporting infrastructure, resulting in inefficiencies in recycling, disposal, and reuse [147, 155]. While these challenges impact the overall efficiency of the EV battery SC, they are less significant than the pressing concerns related to recycling and disposal inefficiencies, as current battery technologies continue to satisfy market demands despite ongoing advancements in design and integration [61, 62, 160].

To address these issues, 51% of the articles propose strategies that include four sub-solutions and 18 broad solutions (Appendix B). From Figure 5, the key strategies involve implementing CE and sustainable practices, adopting intelligent technologies and digital transformation, fostering technological innovation in materials and infrastructure, and utilizing strategic modelling and market analysis to enhance the overall efficiency of battery lifecycle management. This challenge is the third most addressed challenge in the literature, reflecting the critical importance of technological innovation and infrastructure to the industry, which heavily depends on advancements in these areas. Improving technical innovation and infrastructure in EV battery management depends critically on short-term goals including increasing recycling efficiency and material recovery strategies [21]. Using improved sorting methods and standardizing battery recycling technology can greatly increase resource recovery rates [119]. By lowering contamination and enhancing recyclability, the automation of sorting and separation operations can improve the precision of material recovery and guarantee the effective extraction of important materials such as lithium and cobalt [75]. Furthermore,

modernizing recycling facilities with high efficiency crushing and hydrometallurgical techniques would help to minimize waste accumulation and enhance the extraction of important battery components [158-160]. By use of modular, scalable recycling facilities, companies will be able to adapt to changing battery chemistries and hence lower obsolescence risks in material recovery operations [151]. Furthermore, including high-performance diagnostic tools for evaluating battery degradation before recycling will enable best repurposing of second-life batteries, so ensuring that only EOL batteries are handled for material recovery while viable ones are efficiently used [156].

Long-term technical developments should focus on infrastructure enhancements and next-generation battery materials to improve the sustainability of EV battery manufacture and disposal [131]. While increasing battery performance and lifetime, the development of cobalt-free and lithium-sulphur battery chemistries will help to lower reliance on important raw resources [148]. Furthermore, the combination of high-voltage cathodes and solid-state battery designs helps to increase energy efficiency, so enabling longer-lasting batteries and lowering the frequency of replacements, so improving sustainability [116]. Further developments in direct recycling techniques which recover cathode materials without breaking them down into base elements will greatly increase recycling efficiency and material reuse, hence extending a more sustainable battery lifetime [135]. Ultra-fast charging systems and self-healing battery technologies will help to maximize energy storage for EVs, so mitigating performance deterioration and extending battery lifetime [138, 147]. AI-driven predictive maintenance solutions for real-time battery health tracking and optimal disassembly will also guarantee effective EOL processing, therefore supporting a more circular and technologically sophisticated method of battery lifeline management [119, 125].

3.2.1.5. Policy and regulatory frameworks

This challenge refers to the difficulties in developing and establishing regulations that promote the sustainable production, use, and recycling of EV batteries [93, 163]. Twenty-six percent of the reviewed papers address four sub-problems, and eighteen detailed challenges (see Appendix A) related to this issue. The key barriers include implementing regulatory frameworks and ensuring compliance, promoting effective policies, achieving global standards and coordination, and managing risks and oversight. The primary problem is regulatory frameworks and compliance, which directly affect the viability and implementation of all sustainability efforts [145]. The lack of definitive legal frameworks leads to varying rules for

battery lifecycle management, hindering advancements in second-life battery markets, closed-loop recycling systems, and sustainable battery production techniques [38]. Inadequate enforcement, corruption, and regulatory gaps facilitate unsustainable battery disposal and ineffective recycling processes, hence weakening overarching sustainability initiatives [22, 33]. Bureaucratic bottlenecks in the approval of recycling technologies and sustainable production processes hinder innovation and restrict investments in advanced battery designs [45]. Moreover, stringent mining regulations that do not conform to CE concepts exacerbate resource shortages, hence undermining SC resilience and the scalability of sustainable practices [61]. In the absence of a clearly delineated and enforceable regulatory framework, the sector will persist in its difficulties to implement effective sustainability measures, hence extending economic, environmental, and operational inefficiencies throughout the EV battery SC [84, 144].

Among the recognized policy and regulatory obstacles, risk management and supervision issues are comparatively less critical than overarching regulatory flaws [38]. Issues including fire threats, insufficient storage, and environmental pollution present considerable risks [85]. Nonetheless, these risks are predominantly operational and may frequently be alleviated through technology advancements in tracking, handling, and waste management [39, 90]. Consequently, comprehensive regulatory adjustments are not invariably required to resolve these difficulties [93].

Financial limitations associated with restrictive policies impede investment in safer and more efficient recycling technologies; however, alternative funding mechanisms, such as public-private partnerships, can alleviate these constraints without necessitating immediate government intervention [100, 107, 127]. A further moderate issue is attaining worldwide standards and coordination, as the absence of internationally harmonized legislation results in trade fragmentation, variable recycling efficiency, and restricted integration of the CE across markets [72]. Regulatory inconsistencies across areas obstruct the efficient movement of secondary battery materials, resulting in SC inefficiencies that impede economies of scale in recycling and reuse efforts [137, 139]. In the absence of worldwide standardization, manufacturers and recyclers encounter difficulties in formulating uniform sustainability policies, which impacts the long-term feasibility of EV battery circularity [78, 130, 136]. A significant concern is the formulation and promotion of policies, wherein insufficient advocacy for resource sustainability results in excessive consumption, market distortions, and inadequate support for sustainable behaviours [62]. The lack of specific incentives for recycling and sustainable battery production deters companies from embracing CE strategies, hence

heightening reliance on raw material extraction [70]. The absence of adequate subsidies and financial incentives for sustainable technologies diminishes the economic viability of battery recycling operations, hence constraining the expansion of second-life battery applications and efficient material recovery initiatives [78, 154]. In the absence of clearly articulated regulations that promote responsible production, efficient resource use, and CE-oriented market frameworks, industry stakeholders will persist in favouring immediate economic benefits above enduring sustainability goals [100].

To address these challenges, Figure 5 presents four main solutions and seventeen comprehensive solutions (Appendix B) that are identified and discussed in 37% of the publications. These solutions include establishing regulatory standards and ensuring compliance, promoting incentives and market strategies, supporting CE policies, and maximizing resource efficiency while minimizing environmental impact. In the immediate future, enhancing regulatory compliance and enforcement is essential for establishing a consistent standard for the EV battery SC [11]. Prompt enhancements in safety certifications, compliance assessments, and governance frameworks will ensure that battery manufacturing, utilization, and recycling adhere to the highest safety and environmental requirements [29, 36, 37]. Moreover, minimizing bureaucratic inefficiencies by optimizing approval processes for novel recycling technologies and sustainable innovations can facilitate the expedited adoption of environmentally friendly solutions [40]. Economic incentives and market-oriented strategies must be instituted to motivate manufacturers and recyclers to embrace sustainable practices [60, 77, 93]. For example, reward-penalty systems under extended producer's responsibility (EPR) programs can ensure that battery manufacturers are responsible for the management of their goods at the end of their life cycle [54, 55, 56]. Additionally, predictive modelling and market barrier research will enable policymakers to foresee forthcoming economic and environmental issues, facilitating the effective execution of sustainability initiatives within the EV battery sector [102, 105, 124].

Long-term sustainability across the EV battery lifespan necessitates extensive regulatory reforms and worldwide standardization [42, 47, 158]. Aligning worldwide regulatory frameworks will enhance the exchange and repurposing of secondary materials, reducing inefficiencies stemming from disparate recycling policies [57, 145]. Furthermore, promoting CE policies will facilitate the establishment of sustainable production and disposal practices, thereby diminishing reliance on raw material extraction [111, 141, 147]. A vital long-term answer is improving resource efficiency via clearly defined regulatory frameworks that require sustainable resource management and reduce environmental deterioration [150-152].

By establishing robust governance and international cooperation among stakeholders, these policies will foster a stable and sustainable regulatory framework for the production, recycling, and disposal of EV batteries [142, 148, 158].

3.2.1.6. Resource efficiency and alternative materials

The primary challenge in this area is managing material resources effectively from extraction to EOL, while ensuring their use does not compromise environmental sustainability [66,114]. Twelve percent of the papers address nine overall difficulties (see Figure 4 and Appendix A) and two sub-challenges related to resource efficiency and alternative materials. These challenges include issues with unsustainable sourcing practices and the need for innovative and efficient material use. The most significant challenge in resource efficiency and alternative materials arises from the heavy dependence on high-risk materials like cobalt and lithium, which expose the EV battery SC to geopolitical risks, price volatility, and potential shortages [45]. The geographic concentration of these critical resources in politically unstable regions further heightens SC vulnerabilities, making long-term material availability uncertain [60]. The overuse of rare earth elements in battery production leads to environmental degradation and resource depletion, with mining and processing activities generating severe ecological concerns [148]. The lack of sustainable mining practices, including deforestation, water pollution, and habitat destruction, exacerbates the negative impact especially in regions where regulations are weak or poorly enforced [143]. Additionally, the surging demand for lithium is straining global reserves, resulting in inefficient resource allocation and exacerbating supply shortages, which directly hinder scalability and long-term production stability [148]. These factors underscore the urgent need for more sustainable resource management and innovations in alternative materials to ensure the long-term viability of EV batteries [169].

A relatively lesser challenge within resource efficiency and alternative materials is the inefficiency in utilizing alternative battery materials and the complexity of recycling diverse battery chemistries [168]. The lack of standardization across battery designs and materials makes it difficult to establish scalable recycling methods, leading to lower recovery rates and increased waste [61]. Additionally, alternative battery materials such as nickel-rich cathodes and fluoride-based compounds face validation and performance constraints, making their integration challenging without affecting battery efficiency, cost, and lifespan [68]. In some cases, inadequate lifecycle assessments of new materials result in unforeseen environmental consequences, as certain alternatives may require more intensive processing or hazardous

extraction methods [85]. Furthermore, the carbon footprint of battery production is heavily influenced by the energy mix regions dependent on carbon-intensive energy sources undermine the sustainability benefits of EV batteries, making clean energy integration essential for reducing overall environmental impact [97].

Addressing solutions to these challenges, aim to improve resource management and promote the use of alternative materials in a way that supports sustainability throughout the EV battery SC. From Figure 5, 33% of the articles propose solutions, offering four sub-solutions and sixteen comprehensive solutions (Appendix B). CE models and resource optimization tactics can substantially improve material efficiency and sustainability in the short run [40]. Battery remanufacturing and circular business models enable the retrieval of valuable elements from outdated batteries, thereby decreasing the need for newly mined raw materials and mitigating the environmental damage associated with mining operations [45, 48]. Moreover, Giri et al. [71] and Baars et al. [88] underlined that the creation of recycling-compatible battery designs facilitates the disassembly and processing of batteries at the conclusion of their lifespan, enhancing recycling efficiency and minimizing waste. The enactment of closed-loop recycling legislation is a prompt solution, facilitating industries in creating systems for the circular reutilization of materials, so ensuring a consistent supply of essential components like lithium and cobalt while minimizing environmental repercussions [68]. Moreover, cooperation among SC participants is crucial for enhancing recycling processes, increasing material recovery rates, and minimizing inefficiencies in resource use [109]. These initiatives offer a pragmatic and implementable strategy for improving sustainability in the near term, tackling issues related to material shortages and waste management [88].

In the long term, innovations in material science and sustainable design will be essential for diminishing reliance on hazardous materials and improving sustainability [80, 89]. The advancement of alternate battery chemistries, including fluoride-based compounds and high-performance cathodes, would markedly diminish dependence on limited resources such as cobalt and lithium, alleviating supply problems and environmental issues [95]. Moreover, modular battery designs will facilitate the targeted repair and reutilization of battery components, thereby reducing waste and enhancing battery durability and material efficiency [104]. The incorporation of sustainable sourcing procedures will enhance ethical and environmentally responsible extraction, guaranteeing long-term resource availability and minimizing ecological damage [90, 116]. As renewable energy gains prominence, improving energy-efficient manufacturing processes will be crucial for minimizing the carbon footprint of battery manufacture, especially in areas dependent on carbon-intensive energy sources [96,

105, 118]. Through the ongoing enhancement of sophisticated technologies and sustainable practices, the industry can create a robust and self-sustaining SC for EV batteries, thereby guaranteeing long-term resource security and environmental preservation [143, 148, 153].

3.2.1.7. Digital transformation for sustainability

Digital transformation for sustainability challenge includes incorporating advanced digital technologies to enhance sustainability in business operations and improve SC efficiency. This challenge comprises two sub-challenges and nine detailed challenges (see Appendix A) and is covered in 5% of the reviewed articles. Figure 4 shows key issues like predictive analysis and quality tracking as well as the integration of Internet of Things (IoT) and blockchain technologies for resource management. The primary hurdle is the integration of IoT and blockchain technologies for resource management, which encounters substantial implementation obstacles, data accessibility concerns, and a deficiency in standardization [152]. Tavana et al. [151] revealed that IoT-based real-time monitoring can significantly improve battery tracking, energy efficiency, and waste reduction; however, inadequate implementation hinders firms from fully capitalizing on these advantages. Likewise, Júnior et al. [29] displayed that blockchain technology, which has the potential to augment transparency, enhance traceability, and deter illicit market activities, remains inadequately integrated into the SC, resulting in issues such as material misallocation, inefficiencies in tracking end-of-life batteries, and regulatory non-compliance. The absence of integrated digital systems intensifies data silos and transparency deficiencies, complicating the verification of ethically sourced resources and adherence to sustainability standards [161]. In the absence of effective IoT and blockchain ecosystems, organizations face challenges in fulfilling sustainability regulations, which diminishes material recovery efficiency and exacerbates environmental deterioration [162]. Ultimately, these digital deficiencies hinder CE projects, limiting efforts to improve resource recovery, optimize SC efficiency, and ensure long-term sustainability in EV battery management [57].

A less urgent yet significant obstacle in digital transformation for sustainability pertains to predictive analysis and quality control, which are hindered by inaccurate forecasting models that result in wasteful resource allocation and premature disposal of EV batteries [129]. Erroneous forecasts concerning battery performance and longevity lead to superfluous waste production and reduced recovery prospects, thus impacting sustainability initiatives [152]. Furthermore, monitoring inefficiencies in resource flows complicates organizations' ability to

efficiently oversee material utilization, resulting in inaccuracies in production planning, disposal, and recycling processes [152]. The deficiencies in predictive analytics and monitoring impede optimization initiatives and result in heightened waste, loss of essential commodities, and environmental damage [152]. The failure to effectively monitor materials such as lithium and cobalt leads to their disposal in landfills instead of recovery and reuse, exacerbating environmental consequences and diminishing total recycling efficacy [154].

To address these challenges, 4 sub-solutions and 17 comprehensive solutions (see Appendix B) are proposed, as discussed in 22% of the articles. From Figure 5 shows the solutions that focus on leveraging strategic insights and decision-making models, utilizing smart analytics and optimization technologies, and employing mapping and life cycle analysis to improve resource management and sustainability throughout the SC. It can be noted from Table 2 that the percentage of studies addressing digital transformation for sustainability challenges is relatively low, largely due to the emerging nature of these technologies and practices in the context of EV. In the short term, rectifying forecasting inefficiencies and resource tracking can be accomplished using strategic insights, advanced analytics, and digital monitoring systems [160]. Utilization of predictive analytics [24] and Monte Carlo-based sensitivity analysis [139] will improve demand forecasting and material recovery planning, enabling manufacturers and recyclers to more accurately predict the availability of EOL batteries and minimize resource loss. Moreover, AI-driven sorting technologies will enhance the disassembly and classification of battery components, facilitating the effective recovery of important metals like lithium and cobalt [124]. Advanced battery management systems will enable real-time monitoring of battery performance and predict EOL conditions, ensuring prompt collection for recycling and minimizing wasteful disposal [123, 162]. Furthermore, Hua et al. [162] underlined big data analytics and predictive maintenance models will facilitate the early detection of SC inefficiencies, permitting proactive measures prior to the escalation of issues. These digital technologies will enhance the monitoring, tracking, and optimization of resource flows, ensuring that materials are not squandered but reintegrated into the SC [147, 151].

Ultimately, thorough lifetime analysis, blockchain integration, and IoT-enabled optimization models will be crucial for improving transparency, efficiency, and sustainability in the EV battery SC [36, 119]. Lifecycle assessment approaches will offer comprehensive evaluations of the environmental effect associated with battery production, utilization, and recycling, pinpointing potential for sustainability enhancements [50, 101]. Furthermore, geographic information systems and material flow analysis will refine logistics for battery

material recovery, alleviating bottlenecks and improving worldwide recycling efficacy [116]. Integrative sustainability assessment frameworks will progressively allow industries to reconcile environmental, economic, and social aspects, resulting in enhanced decision-making in production and recycling [119]. Blockchain technology will enhance traceability and regulatory compliance, facilitating secure tracking of battery materials from manufacture to disposal while mitigating data tampering and non-compliance with CE regulations [163]. IoT-based optimization models will offer real-time insights into resource flows, enhancing coordination among supply, recycling, and disposal networks, thus promoting a completely integrated and digitally optimized SC for EV batteries [53, 164]. These long-term innovations will ultimately establish a transparent, efficient, and resource-conserving SC for the EV battery sector [139].

3.2.1.8. Research and systematic analysis

This challenge involves the thorough scrutiny and systematic evaluation of current processes, technologies, and practices within the SCSC [78]. Barriers to research and systematic analysis include four sub-challenges and 16 comprehensive challenges (see Appendix A), which are covered in 10% of the reviewed articles. Figure 4 depicts key problems that are identified from articles are technological development and adoption challenges, data gaps and methodological limitations, economic and market factors, and issues related to collaboration and emerging research. A significant obstacle to methodical research initiatives is the volatility of research financing, predominantly influenced by economic and market variations [142]. Feng et al. [74] highlighted market volatility affects research investment in sustainable technologies, as fluctuating raw material prices, market uncertainties, and regulatory changes generate financial unpredictability, hence constraining long-term funding for systematic analysis and development projects. Moreover, Zhu et al. [72] pointed policy-driven incentives like environmental fees and the elimination of subsidies create additional uncertainties, especially when implemented inconsistently across various locations. The inconsistency in financial support adversely affects the development of innovative recycling methods and lifecycle evaluations, hindering industries from attaining sustainable production and resource efficiency [91, 96]. These economic limitations deter business and governmental entities from dedicating resources to thorough scientific assessments, thereby restricting the development of dependable sustainability indicators and standards [167].

Additional primary obstacle arises from technology advancement and implementation, since the substantial expenses and gradual integration of modern recycling technologies impede the systematic assessment and enhancement of sustainability solutions [45]. Numerous EV battery recycling and recovery technologies are still inadequately developed, hindering the collection of essential performance data required for efficient research and optimization [74]. Moreover, disparities in technological advancements related to supplier development and integration strategies among EV manufacturers lead to variable recycling rates, hence complicating research efforts [74].

The issue is exacerbated by data deficiencies and methodological constraints, as the lack of empirical evidence and variations in environmental effect assessments hinder the establishment of established criteria for battery recycling efficiency [96, 142]. Divergences in battery health forecasts, carbon footprint evaluations, and recycling emission coefficients result in disjointed study outcomes, complicating the establishment of dependable best practices [57]. Llamas-Orozco et al. [167] indicated that absence of standardized lifecycle assessment approaches across international markets generates ambiguity in assessing sustainability consequences, hindering widespread implementation of efficient recycling practices. Resolving these difficulties necessitates increased investment in sophisticated data collection methods, lifecycle analysis instruments, and defined performance indicators to enhance transparency and trustworthiness in research results [45].

A relatively minor yet consequential problem in research and systematic analysis is the deficiency of international collaboration and knowledge transfer, which obstructs the advancement and implementation of efficient recycling technologies within SCSC [144]. The lack of synchronized knowledge transfer between industries and academia hinders the adoption of new technologies, resulting in postponements in the implementation of optimal practices in battery recycling and material recover [149]. Moreover, a lack of comprehensive systematic research on developing recycling technologies impedes worldwide information transmission, hence limiting the scalability of sustainable recycling methods [150]. In the absence of robust collaboration frameworks, advancements in sustainable EV battery recycling are disjointed, hindering overall enhancements in efficiency, cost-effectiveness, and environmental sustainability across the industry [149].

Solutions for addressing these risks include 4 sub-solutions and 17 detailed solutions (see Appendix B), discussed in 25% of the literature (see Figure 5). The key approaches like the application of research methodologies and analysis tools, integrating innovative and advanced technologies, implementing efficient strategic planning and SC management, and

ensuring appropriate incentives and policy frameworks are in place to support systematic research and analysis efforts. In the upcoming future, enhancing research methodology and analytical instruments is essential for mitigating data limitations and discrepancies in assessing the environmental and economic effects of EV battery recycling [64, 77]. Standardizing approaches like LCA and material LCA enables researchers to guarantee uniform data collection and enhance the accuracy of evaluations regarding material flows and recycling efficiency [43]. Sathre et al. [148] underlined, the implementation of parameter uncertainty quantification and sensitivity analysis improves the accuracy of forecasts concerning battery degradation, material recovery, and resource utilization. Chen et al. [163] underscored these solutions enable firms to swiftly modify recycling programs using dependable data, hence enhancing decision-making in sustainable resource management. Technological improvements, such automated sorting technologies and sophisticated battery control systems, can be swiftly integrated to enhance material separation, reduce waste, and maximize recycling rates [130, 131]. Implementing these technologies in pilot programs and focused studies facilitates their gradual enhancement and incorporation into extensive operations, guaranteeing immediate improvements in recycling efficiency and methodical research methods [99, 100].

In the long term, strategic planning and SC management will be essential in establishing a resilient and adaptive EV battery SC [167]. A rigorous examination of infrastructure optimization can guarantee effective resource allocation, mitigating the hazards of SC interruptions and material deficiencies [167]. Investigating second-life applications for batteries, including energy storage systems, may postpone recycling while optimizing resource utilization, resulting in a more sustainable SC model [31]. Moreover, Zeng et al. [46] highlighted that the advancement of adaptable recovery methods via ongoing R&D will facilitate recycling procedures to align with changing battery chemistries, hence ensuring long-term sustainability. Financial incentives and legislative frameworks are essential to stabilize research funding and promote ongoing investment in sustainable production methods [38, 113]. Establishing universal standards for research methodology and aligning sustainability initiatives across businesses will promote efficient knowledge exchange, ensuring that technical innovations move from theoretical frameworks to practical application [44, 157]. These activities will establish a long-term, data-driven framework for sustainable EV battery recycling and resource recovery [157].

3.2.1.9. Social and legal implications

This challenge involves ensuring ethical practices, compliance with societal norms, and addressing regulatory issues that arise throughout the lifecycle of EV batteries [59]. The social and legal implications barrier includes three sub-challenges and 11 comprehensive challenges (see Appendix A), covered in 10% of articles. This includes issues related to labour and employment, community and cultural impacts along with ethical sourcing and compliance. Community dislocation and the loss of cultural heritage pose considerable social and legal challenges [68]. Extensive mining and recycling activities frequently necessitate the forced displacement of communities, resulting in economic instability and social turmoil [78]. In other instances, displaced communities have initiated legal actions or organized protests, resulting in project delays and heightened operational expenses [82]. The obliteration of historically and culturally valuable sites intensifies resistance from local communities and international advocacy organizations, hence escalating legal disputes and public dissent [152]. Petavratzi et al. [152] indicated that absence of inclusive decision-making and participatory frameworks exacerbates concerns, as residents are frequently marginalized from essential conversations regarding mining, processing, and recycling initiatives. In the absence of transparent stakeholder participation and equitable compensation methods, disputes endure, resulting in extended legal conflicts and reputational damage for firms operating in contentious regions.

The failure to synchronize industrial operations with community expectations and cultural sensitivities remains a significant yet controllable barrier in the EV battery SC. The foremost social and legal dilemma is to labour and employment issues, which carry significant ethical and operational implications throughout the SC. The exploitation of workers, encompassing child labour, inadequate remuneration, and perilous working conditions, persists in areas where raw minerals such as cobalt and lithium are sourced [22]. These unethical labor practices incite social instability, regulatory examination, and public denunciation, resulting in strikes, labour shortages, and legal conflicts that impede SC operations [58]. Moreover, hazardous working conditions in battery manufacturing and recycling elevate the incidence of workplace accidents, leading to compensation claims and regulatory penalties [64]. Discriminatory hiring practices, salary discrepancies, and unequal access to work prospects exacerbate socioeconomic inequality, heightening the risk of litigation over employment equity legislation [21]. Tang et al. [98] emphasized that intensifying labour disputes pose considerable reputational and financial concerns, affecting the long-term sustainability and public perception of enterprises engaged in EV battery manufacturing and recycling. Addressing worker rights,

health, and safety is the most pressing and essential factor in alleviating social and legal ramifications in the SC [82].

The least major, yet still impactful, difficulty with social and legal ramifications is ethical sourcing and compliance, which entails assuring responsible procurement methods and adherence to environmental and labour regulations [22]. Numerous firms grapple with unethical sourcing, characterized by unscrupulous mining techniques, substandard labour conditions, and environmental infractions [58]. Organizations that neglect to maintain ethical standards face financial penalties, trade limitations, and reputational harm [93]. Non-adherence to recycling legislation and dependence on ineffective, subsidy-based programs exacerbate the problem, resulting in legal conflicts and societal burdens [98]. Furthermore, Kumar et al. [123] underlined that improper battery disposal and insufficient recycling infrastructures intensify health risks and subject companies to legal repercussions, particularly in developing countries where environmental legislation may be inadequate or poorly enforced. Moreover, data privacy issues in digital monitoring systems pose further dangers, as illegal data sharing or security breaches may result in litigation, penalties, and erosion of stakeholder trust [147]. Although these challenges do not currently impede the SC, their prolonged effects on corporate operations, regulatory adherence, and stakeholder trust necessitate attention [98].

Addressing these challenges requires implementing four sub-solutions and 14 comprehensive solutions (see Appendix B), as noted in 17% of the literature (see Figure 5). These solutions focus on establishing collaborative policies and standards, increasing public awareness and education, promoting compliance and fair labour practices, and enhancing transparency and social well-being. Dealing with these issues requires a quick response via cooperative rules and enforced regulations [51]. Establishing a regulatory framework with well-defined rules on worker rights, environmental protection, and community involvement guarantees that every stakeholder follows ethical and legal norms all around the EV battery SC [168]. Global labour and environmental standards established by cooperative projects among governments, businesses, and international organizations help to lower market fragmentation and support responsible sourcing policies by means of their implementation [31]. Strong regulatory compliance systems, according to Melin et al. [95], inspired more industry responsibility; open communication between businesses and legislators helps to align policies and increase policy execution effectiveness. Moreover, proactive involvement with impacted populations can help to avoid legal disputes and lessen societal opposition [142].

Public awareness campaigns and educational initiatives aiming at ethical battery disposal and appropriate recycling constitute another temporary strategy [160]. By means of

educational campaigns on battery EOL management and customer involvement in take-back programs, material recovery efficiency is enhanced and collecting rates are raised [95]. Understanding the effects of inappropriate disposal helps consumers to participate in sustainable recycling practices, therefore supporting the CE concept [95]. Moreover, bolstered should be compliance policies and legal enforcement systems to guarantee ethical employment practices and appropriate waste disposal [31]. Strong labour protection rules and incentive-based recycling legislation help to lower unethical procurement methods and support sensible material recovery techniques [155].

The EV battery sector must build strong transparency and social well-being projects to produce ethical and legally compliant SCs for sustainability over long terms [155]. Using multi-objective models with social effect assessments would help to direct decisions and guarantee that ethical issues always take front stage in SC planning [51]. Mota et al. [51] underlined that include social impact measures into SC assessments enhances openness and enables companies to match ethical sourcing policies and responsible community involvement programs. Clear corporate reporting on social and environmental performance can also help to build regulatory compliance and stakeholder confidence [155].

Another long-term plan centres on cooperative stakeholder integration to propel ethical SC governance. Formal alliances between manufacturers, recyclers, legislators, and community groups will help to establish harmonized labour regulations, ethical sourcing agreements, and uniform legal compliance rules [40]. Collaborative policies are essential for creating a robust foundation for sustainability which guarantees fair involvement in decision-making procedures, therefore reducing social conflicts and possible litigation [51]. Moreover, international cooperation can help to create uniform policies for ethical procurement, conscientious recycling, and compliance monitoring, so lessening the dispersion of regulatory systems over several countries [166].

3.2.1.10. Industrial process efficiency

This challenge emphasizes areas where the industry must improve efforts to achieve more efficient and sustainable production and recycling processes [117]. The Table 2 presents the barriers related to industrial process efficiency include two sub-challenges and five comprehensive challenges (see Figure 4 and Appendix A), discussed in 14% of the articles. Key barriers include manufacturing process optimization challenges and CE and waste minimization issues (see Figure 4). The primary obstacle to attaining industrial process

efficiency is the optimization of manufacturing processes, especially for the substantial material and energy consumption involved in battery production and recycling [28]. Excessive energy consumption elevates GHG emissions and operational expenses, compromising the environmental advantages of EV and engendering long-term sustainability challenges [84]. The substantial energy requirements for battery production necessitate considerable technological progress to reconcile industrial productivity with energy efficiency; nevertheless, the expense of adopting such technologies is frequently excessive [148-150]. Furthermore, Jiang et al. [91] underlined those logistical inefficiencies, like the geographical separation between battery dumping locations and recycling facilities, exacerbate transportation expenses, delays, and overall inefficiencies in material recovery. The intricate disassembly and sorting procedures necessary for extracting important elements such as lithium and cobalt diminish material recovery rates, compelling manufacturers to depend on fresh raw materials rather than recycled components [87, 88]. The inefficiencies in production and recycling workflows generate bottlenecks, elevate downtime, and obstruct production continuity, rendering this sub-challenge the paramount issue in industrial process efficiency [89].

The least significant difficulty in industrial process efficiency is the inadequate use of CE principles and suboptimal waste reduction measures within the EV battery sector [79]. Material losses, ineffective recycling methods, and insufficient tracking systems result in low recovery rates of valuable materials, hence heightening dependence on virgin resources and intensifying trash generation [50]. Li et al. [96] revealed that misalignment among stakeholders and insufficient coordination among recyclers, manufacturers, and legislators impede the advancement of efficient closed loop recycling systems, hence diminishing the overall efficacy of the industrial SC [131]. Slattery et al. [90] indicated that the lack of comprehensive data tracking and monitoring technologies limits visibility into battery composition, usage patterns, and remaining capacity, hindering the optimization of recycling and reuse initiatives. In the absence of enhanced tracking systems, manufacturers find it challenging to recognize opportunities for material recovery and waste minimization, leading to significant environmental repercussions and inefficiencies in resource use [81, 99].

To address these challenges, 35% of the literature proposes 4 main sub-solutions and 20 in-depth solutions (Appendix B). These solutions focus on optimizing production processes, developing sustainable materials and battery technologies, enhancing SC networks and efficiency, and advancing sustainable recycling practices. In the short term, enhancing manufacturing processes and incorporating cleaner production technologies are critical measures for augmenting industrial process efficiency in the EV battery SC [95]. Employing

advanced production line configurations and virtual modelling tools enables businesses to simulate and optimize production workflows, detecting inefficiencies prior to the commencement of actual manufacturing [112]. These sophisticated digital methodologies facilitate operational efficiency, minimize material waste, and improve resource use [100]. Furthermore, using cleaner industrial technologies, including low-emission processing techniques and waste reduction strategies, can promptly reduce environmental impact and decrease operational expenses [153-155]. These focused enhancements guarantee immediate increases in production efficiency, waste minimization, and cost optimization, establishing a basis for enduring industrial progress [131, 144, 148].

In the long future, sustainable material development, improved SC networks, and sophisticated recycling methods will be essential for enhancing industrial process efficiency in EV batteries [59, 67]. Investigating alternate materials and battery modularization methods can yield more durable and efficient battery designs, decreasing reliance on limited resources and extending battery lifespan [114]. Moreover, enhancements in SC optimization and risk management can bolster SC resilience by facilitating effective procurement, transportation, and production coordination [120, 167, 168]. The incorporation of CE concepts via sustainable battery design emphasizing ease of disassembly, reparability, and recyclability guarantees prolonged utilization of battery components, therefore substantially diminishing the demand for raw materials [147]. These long-term plans will create a more sustainable and resource-efficient industrial process, promoting ongoing improvements in battery production, recycling, and SC sustainability [73].

3.2.2. Innovative technologies

This section addresses Objective 2 of the study by focusing on the identification and analysis of innovative technologies capable of addressing the previously mentioned challenges and enhancing resource efficiency. Table 3 depicts the analysis that reveals 7 main innovative technologies, 24 sub-technologies, and 105 detailed technologies (Appendix C). Recycling and material processing technologies are the most extensively researched category, including 46% of publications, with four sub-technologies and 24 specific technologies (see Appendix C) dedicated to specialized recycling processes, battery lifecycle management, improved network designs, and material recovery techniques. This underscores the increasing significance of automated waste management and adherence to regulations. Conversely, automation and robotics have the least study coverage (6%), encompassing 2 sub-technologies and 4 detailed

technologies (see Appendix C), mostly functioning as auxiliary technologies for battery component separation, sorting, and enhancing recovery rates. Innovation technologies in SC are addressed in 27% of research, divided into three sub-technologies and 21 specific technologies, with the objective of enhancing logistics, network modelling, and SC management. Advanced sorting and classification technologies (7%) comprise 4 sub-technologies and 11 detailed technologies, improving recycling efficiency via sophisticated sorting systems, intelligent classification, and analytical instruments. Likewise, eco-friendly technologies (27%) comprise two sub-technologies and ten specific technologies (see Appendix C) that advance sustainable material extraction and processing methods. Battery technologies, the second most investigated category (37%), encompass four sub-technologies and fifteen specific technologies (see Appendix C), addressing advancements in battery chemistry manufacturing processes, battery management systems, and second-life applications. Digital transformation (14%) consists of three sub-technologies and eleven specific technologies (see Appendix C), utilizing IoT, cloud computing, and data analytics to optimize industrial processes and improve transparency. Finally, advanced technical innovation and infrastructure (28%) encompass two sub-technologies and nine specific technologies (see Appendix C), concentrating on strategic planning models and intelligent digital systems to enhance EV battery production, recycling, and sustainability.

Table 3
Identification and classification of innovative technologies of SCSC for EV batteries.

Innovative technologies	Sub- technologies	No. of studies (%)
1) Recycling and material processing	a) Direct and specialized recycling methods b) Battery lifecycle management and repurpose c) Advanced network and system design d) General recycling processes and materials recovery	46%
2) Automation and robotics	a) Disassembly systems b) Planning and optimization	6%
3) SC innovation	a) Design and optimization strategies b) Network and modeling approaches c) Innovative technologies for SC management	27%
4) Advanced sorting and classification	a) Advanced sorting systems b) Smart classification methods c) Separation and diagnostic technologies d) Analytical and spatial tools	7%
5) Eco-friendly technologies	a) Material extraction and processing technologies b) Management technologies	27%
6) Battery technologies	a) Battery chemistry and production b) Battery management and diagnostics c) Battery design and manufacturing d) Battery applications and second life uses	37%
7) Digital transformation	a) Life cycle and CE tools b) IoT and cloud-based services c) Data analysis and modeling	14%

8) Advanced technological innovation and infrastructure	a) Strategic insights and planning models b) Digital systems and smart technologies	28%
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3.2.2.1. Recycling and material processing technologies

Recycling and material processing technologies are essential for improving material recovery, cost-effectiveness, and sustainability within the EV battery SC [11]. Direct recycling techniques, including cathode recycling, mechanochemical processes, and froth flotation, facilitate the high-purity recovery of precious materials while markedly decreasing energy consumption and material waste [150]. AI-powered lifecycle management solutions, encompassing cognitive digital twins and predictive maintenance models, provide real-time monitoring, failure forecasting, and optimal second-life applications, ensuring batteries are effectively repurposed prior to the recycling phase [55]. Hydrometallurgical and pyrometallurgical methods continue to be the primary techniques for large-scale battery recycling, efficiently processing heterogeneous chemistries [72]. Recent improvements in sustainable leaching techniques seek to reduce harmful consequences and energy-intensive processes [166]. Furthermore, Tavana et al. [151] emphasized that enhanced collection and network systems, including EOL vehicle recycling networks, collaborative logistics models, and automated sorting technologies, are improving the efficiency of battery material collection, transportation, and processing, thereby ensuring a cost-effective and sustainable material flow throughout the SC.

Every recycling method has trade-offs in efficiency, environmental impact, and scalability [58]. Direct cathode recycling and mechanochemical techniques preserve active materials, reducing energy-intensive refining and improving recovery, but they require precise sorting and advanced diagnostic and material-tracking technologies [170]. Hydrometallurgical recycling, such as chemical leaching, can process diverse battery chemistries [166] but generates secondary chemical waste that necessitates additional treatment, posing environmental concerns [171]. Pyrometallurgical recycling, while enabling high-speed metal extraction and large-scale processing [72], is less sustainable due to high energy consumption and CO₂ emissions [171]. AI-driven battery lifetime management systems, including cognitive digital twins, enhance, automatic defect detection, and optimal reuse, outperforming traditional monitoring methods which are easier to implement [55, 151] but lack real-time tracking that often leading to premature battery disposal [172]. Automated collection networks and AI-driven logistics models improve tracking accuracy, material flow, and cost efficiency [123] but

require substantial infrastructure investments and regulatory support [172], whereas conventional waste management methods, though more affordable, suffer from inefficient material monitoring, causing delays, resource loss, and suboptimal recycling outcomes [90]. As AI, automation, and sustainable recycling technologies evolve, they will drive a circular battery economy that is more efficient, scalable, and environmentally sustainable, with direct recycling reducing reliance on virgin materials and energy-intensive processing [80] while AI-driven lifecycle management maximizes battery utilization, repurposing, and recycling before material recovery [172].

The long-term incorporation of recycling and material processing technologies will foster a more sustainable, efficient, and circular battery economy [61]. The evolution of hydrometallurgical recycling will shift towards sustainable leaching techniques, reducing detrimental byproducts while improving the recovery efficiency of lithium, cobalt, and nickel [52]. Automated sorting, collection, and logistics systems will enhance recycling operations, minimizing transportation emissions and processing delays, hence optimizing material flow for cost-effectiveness and efficiency [11, 101]. Furthermore, advanced electrode designs will integrate enhanced disassembly and recyclability, markedly reducing material recovery expenses and streamlining battery recycling procedures [144]. Integrating advanced AI-driven optimization and automated recycling infrastructure will transform the EV battery SC into a self-sustaining, resource-independent, and climate-resilient ecosystem, ensuring long-term sustainability in EV production and recycling [60].

3.2.2.2. Automation and robotics

Automation and robotics are revolutionizing the SCSC of EV batteries by enhancing efficiency, accuracy, and safety in disassembly and material recovery [11]. Automated disassembly systems and robotic disassembly facilitate the efficient deconstruction of battery modules, enabling the accurate retrieval of essential elements while minimizing human exposure to toxic compounds [80]. These solutions minimize material loss and improve the recovery rate of reusable components, facilitating closed-loop battery manufacture [11]. Disassembly sequence planning enhances the systematic breakdown of EV batteries, facilitating effective resource recovery while minimizing waste and energy expenditure [160]. Furthermore, sophisticated mathematical models that include carbon emissions are being included into automation systems to assess sustainability criteria and enhance low-emission, energy-efficient disassembly operations in battery recycling [125]. Compared to manual

sorting, automated disassembly significantly enhances efficiency and safety, though it requires substantial capital investment and sophisticated machine learning algorithms for precise operation [60]. Similarly, AI-powered robotic arms outperform traditional mechanical sorting methods by offering greater adaptability and consistency [72, 79]; however, they come with the challenge of high maintenance costs and increased technical complexity [79].

Automation and robots in the EV battery circular SC provide considerable benefits compared to conventional human disassembly techniques [79], but they also pose issues concerning cost, adaptability, and deployment [173]. Automated disassembly systems offer superior precision, accelerated processing, and improved worker safety [60]; but they necessitate substantial capital investment and require frequent updates to adapt to changing battery designs [173]. Robotic disassembly enhances precision and efficiency [130]; yet its efficacy relies on AI-driven adaptation to manage diverse battery chemistries [173]. Conversely, manual disassembly techniques exhibit more adaptability to various battery types without necessitating expensive infrastructure [72]; but they are labour-intensive, time-consuming, and pose risks to workers due to exposure to toxic materials [173]. Disassembly sequence planning facilitates systematic and efficient disassembly, minimizing energy expenditure and waste [160]; yet it depends on the integration of real-time data and the standardization of processes [174]. Mathematical models for carbon-aware automation facilitate the alignment of battery disassembly with sustainability goals [76, 125, 158]; however, these models necessitate validation via extensive deployment to achieve optimal efficacy in industrial recycling systems [151].

In the longer term, automation and robotics will transform battery disassembly and material recovery, improving efficiency, adaptability, and environmental sustainability [79]. Automated disassembly systems will incorporate sophisticated AI and machine learning algorithms, enabling them to adjust to changing battery designs with minimal oversight [79]. Robotic disassembly technologies will enhance accuracy, processing velocity, and material recovery rates, guaranteeing the effective reclamation and repurposing of high-value materials [138]. Disassembly sequence planning models will advance to include real-time monitoring and adaptive sequencing, optimizing resource recovery and minimizing process inefficiencies [160]. Furthermore, carbon-aware mathematical models will facilitate low-emission disassembly solutions, thereby aligning automation-driven recycling with environmental policies and industrial sustainability objectives [158]. The integration of robotics, AI-driven process optimization, and structured disassembly frameworks will enhance material efficiency, decrease operational costs along with improving compliance with sustainability standards in

the EV battery SC, thereby ensuring long-term progress in battery lifecycle management and production [145, 173].

3.2.2.3. Supply chain innovation

Innovative technologies in SC are revolutionizing logistics, resource distribution, and sustainability through the integration of digitalization, sophisticated modelling, and network optimization to enhance efficiency, traceability, and resilience [36]. Design and optimization tools, including network flow optimization, big data analytics, and genetic algorithms, boost material distribution, minimize costs, and improve recycling networks by assessing real-time supply and demand variations [77, 156]. Network and modelling methodologies, such as Stackelberg game theory, geographic information system -based tracking, and material flow analysis, offer strategic frameworks for decision-making to alleviate risks and disruptions [133]. These models enable stakeholders to anticipate and adapt to economic variations, geopolitical restrictions, and environmental constraints [39]. Moreover, IoT, blockchain, and Radio frequency identification for enhanced battery traceability [55, 123]. Tracking technologies improve real-time monitoring, fraud deterrence, and adherence to sustainability regulations by facilitating the continuous tracking of battery materials from raw extraction to EOL recycling [124].

SC innovation technologies have unique benefits and compromises for their efficiency, adaptability, and difficulty of application [58]. Big data analytics and network optimization methodologies facilitate real-time predictive decision-making [151]; however, they necessitate substantial computational resources and a well-integrated infrastructure [175]. Genetic algorithms improve SC efficiency by optimizing logistics flows [77]; yet they lack resilience to unforeseen disturbances without the incorporation of real-time data [92]. Multiplex and multilayer network models offer an in-depth comprehension of SC resilience [75]; yet they necessitate intricate computer processing and regular recalibration to maintain efficacy [176]. Blockchain and IoT enhance SC transparency and security by providing tamper-proof, decentralized tracking of items [123]; however, they encounter integration issues stemming from interoperability and regulatory limits [122]. Geographic information system -based tracking and material flow analysis models facilitate precise spatial monitoring [133]; however, their efficacy is unexpected upon correct data and interoperability with current SC systems [153, 177]. Some systems prioritize real-time tracking and security [162], while others improve

optimization and predictive modelling, rendering them appropriate for certain SC management objectives [41, 42].

The prolonged advancement of SC innovation technologies will result in a more robust, data-centric, and sustainable SC by optimizing logistics efficiency, diminishing emissions, and augmenting material traceability [101]. AI-driven SC optimization models will enhance logistics planning, decrease energy consumption associated with transportation, and save costs by persistently learning from historical and real-time data [143]. Blockchain and IoT-based monitoring solutions will establish the industry standard for SC integrity, assuring adherence to growing regulatory laws and principles of the CE [29]. Machine learning algorithms will enhance the precision of predictive modelling, enabling SC managers to foresee risks, optimize resource allocation, and make pre-emptive decisions [80]. With the expansion of automation and digitization, the EV battery SC will evolve into an integrated, self-optimizing ecosystem, guaranteeing enhanced sustainability, cost-effectiveness, and operational efficiency in material procurement, production, and recycling [80].

3.2.2.4. Advanced sorting and classification

Advanced sorting and classification technologies are essential for improving material recovery efficiency in the EV battery recycling process by enhancing sorting accuracy, separation precision, and diagnostic capabilities [79]. Sensor-driven sorting and automated visual systems provide immediate recognition and categorization of battery materials, hence minimizing contamination in the recycling process [151]. Intelligent classification techniques, such as machine learning-driven multi-dimensional classification, enhance sorting precision by more adeptly identifying material compositions compared to conventional methods [69, 78, 79]. Moreover, spatially limited multivariate clustering facilitates the automatic categorization of battery components according to their chemical and physical attributes, hence enhancing material recovery efficiency [81]. Separation and diagnostic methods, including flotation and electrostatic separation, enhance material purity by effectively segregating conductive from non-conductive particles [137]. Moreover, electrochemical impedance spectroscopy and equivalent-circuit models offer comprehensive insights into battery health, facilitating the efficient categorization of batteries for second-life applications [78].

Various sorting and classification technologies present distinct advantages and disadvantages regarding accuracy, cost, and scalability [154]. Sensor-based sorting and automated vision systems offer rapid and accurate material identification [165]; nevertheless,

they necessitate significant investment in AI-driven recognition technologies and may be constrained by inconsistencies in material surface characteristics [173]. Classification techniques based on machine learning enhance adaptability and precision in sorting [79]; but they rely on extensive, high-quality datasets for model training and validation [178]. Flotation separation and electrostatic separation are efficient methods for isolating important battery components [31]; however, flotation procedures are significantly influenced by chemical conditions, while electrostatic separation is less successful for tiny particles [179]. Advanced diagnostic instruments such as electrochemical impedance spectroscopy and equivalent-circuit models deliver comprehensive battery evaluations [78]; nonetheless, they necessitate specialist knowledge and advanced apparatus for industrial-scale operation [180].

In long term, the incorporation of AI-driven sorting, automation, and diagnostic tools will markedly improve efficiency, precision, and scalability in the recovery and reuse of battery materials [138]. Upcoming sensor-based sorting systems will include enhanced imaging resolution and spectral analysis, thereby augmenting real-time classification precision [151]. Machine learning algorithms will progress, resulting in self-learning categorization models that can dynamically modify sorting parameters based on real-time input [78]. Flotation and electrostatic separation will grow more sophisticated and versatile, enhancing processing velocities and minimizing material loss [60]. Advanced diagnostic instruments, including electrochemical impedance spectroscopy and equivalent-circuit model, will be comprehensively incorporated into sorting facilities, enhancing the identification of second-life batteries and optimizing material reutilization [78]. Ultimately, these technologies will provide a highly efficient, low-waste circular battery economy, optimizing resource recovery while minimizing environmental effect [79].

3.2.2.5. Eco-friendly technologies

These technologies are revolutionizing the battery industry by facilitating low-impact material extraction, sustainable processing, and environmentally responsible lifecycle management [22]. Direct lithium extraction reduces water usage and chemical application relative to traditional mining methods, rendering it a more sustainable option for lithium recovery [157]. Eco-friendly leaching solutions for hydrometallurgical processes diminish dependence on hazardous chemicals, so assuring a reduced environmental impact while preserving excellent recovery efficiency [79]. Moreover, selective leaching optimizes efficiency by concentrating on battery constituents, hence enhancing material purity and

minimizing waste [137]. Innovative enzyme-based systems include biodegradable components into battery architecture, presenting possible improvements in non-toxic, environmentally sustainable energy storage options [129].

Eco-friendly technologies offer distinct benefits and drawbacks for efficiency, scalability, and sustainability [22]. Direct lithium extraction and selective leaching methods enhance material recovery and mitigate environmental harm, although necessitate sophisticated filtration systems and process optimization for widespread implementation [171]. Green leaching methods mitigate harmful emissions and decrease chemical waste; however, issues persist regarding scalability and cost-effectiveness for industrial applications [171]. Enzyme-assisted battery systems give a novel, biodegradable option; however, they remain in preliminary research phases, with restricted practical viability currently [181]. Industrial symbiosis frameworks promote the reutilization of waste and the sharing of resources among businesses; nevertheless, their efficacy relies on inter-sector collaboration and the seamless integration of logistics [134].

The extensive implementation of sustainable technology will propel the battery sector towards low-carbon, resource-efficient, and environmentally responsible manufacturing and recycling practices [51]. Sustainable material extraction methods will become the norm, substantially diminishing the ecological impact of lithium, cobalt, and nickel mining [42]. Innovative green chemistry solutions will supplant conventional hazardous methods, thereby reducing emissions and waste production [137]. Biodegradable and enzyme-based battery components will facilitate the development of next-generation, eco-friendly energy storage technologies [29]. Principles of the CE will be thoroughly integrated into battery design and recycling systems, guaranteeing the continuous reuse of components with minimal resource exhaustion [86]. Ultimately, these innovations will create a comprehensive sustainable battery ecosystem, bolstering worldwide initiatives aimed at attaining carbon neutrality and enduring environmental stability [165].

3.2.2.6. Battery technologies

Battery technologies are advancing swiftly to improve energy storage, performance, and sustainability in EV applications [21]. Advancements in battery chemistry, including high-nickel, non-cobalt cathodes and silicon anodes, are diminishing dependence on rare and costly raw materials while enhancing energy density and longevity [46]. Solid-state batteries signify a significant innovation by substituting liquid electrolytes with solid alternatives, providing

enhanced safety, superior energy efficiency, and increased longevity [168]. Moreover, advancements in electrolyte manufacturing are enhancing battery stability and temperature resistance, hence diminishing degradation risk and extending overall battery lifespan [145]. Technologies for battery management and diagnostics are progressing, facilitating real-time monitoring and predictive maintenance [29]. State of health assessment technologies provide precise examination of battery performance, enabling manufacturers and users to enhance battery longevity [90]. Advanced battery management systems incorporate artificial intelligence and machine learning algorithms to assess charging trends, forecast faults, and improve efficiency [40]. Simultaneously, innovative battery designs and high-capacity combinations are advancing energy storage capabilities, facilitating extended-range EVs and enhanced battery cycle longevity [82].

Diverse battery technologies offer distinct benefits and compromises concerning cost, energy density, longevity, and sustainability [33]. High-nickel, non-cobalt cathodes improve energy storage capacity [86] but pose issues related to raw material supply and pricing fluctuations [179]. Silicon anodes enhance battery capacity but have expansion problems, necessitating structural adjustments for sustained stability [101]. Solid-state batteries provide enhanced safety and energy density but encounter obstacles in mass manufacture and cost minimization [182]. State of health assessment technologies guarantee precise performance monitoring [90]; however, they necessitate advanced sensors and data integration for optimal functionality [182]. Battery swapping and remanufacturing technologies facilitate prolonged utilization of EV batteries; nonetheless, their widespread acceptance relies on standardization and infrastructural advancement [122].

Long-term progress in battery chemistry, diagnostics, and design will result in more efficient, durable, and sustainable energy storage options [11]. Innovations in solid-state and silicon-based batteries will enhance energy efficiency and accelerate charging times, rendering EVs more accessible and feasible for consumers [168]. AI-driven battery management systems and state of health diagnostics will improve battery reliability and predictive maintenance, minimizing waste and promoting CE practices [40]. Second-life applications, such as battery energy storage systems and remanufacturing solutions, will enhance sustainability by recycling EV batteries for alternate energy storage uses [146]. These developments will cultivate a future in which battery technologies optimize efficiency and reduce environmental impact, thereby fostering a more sustainable and resource-efficient EV ecosystem [46].

3.2.2.7. Digital transformation

Digital transformation technologies are transforming SC management, CE practices along with battery lifecycle optimization through the integration of data-driven decision-making, cloud infrastructure, and real-time analytics [69]. The life cycle and CE tools, including the circularity scoring system, LCA methodology and Brightway2 framework [143, 164], provide thorough studies of environmental impacts and sustainability in battery manufacture and recycling. The Swave matrix tool improves decision-making in sustainable SC management by delineating the economic, environmental as well as social effects of material flows [87]. Moreover, collaborative collection service systems enhance battery take-back initiatives, optimizing reverse logistics efficiency and material recovery rates [88]. The amalgamation of IoT and cloud-based services is augmenting real-time monitoring, traceability, and predictive analytics in manufacturing and circular SCs [69]. The IoT-based SC information architecture enables automated monitoring of battery materials from extraction to recycling, assuring adherence to sustainability rules and operating efficiency [151]. Cloud-based services in manufacturing provide remote monitoring, resource optimization, and decentralized data processing, enabling firms to reduce waste, enhance production efficiency, and improve collaboration across global SC networks [162].

Digital transformation technologies have diverse benefits and obstacles regarding efficiency, scalability, and data integration [162]. LCA technologies such as brightway2 and Greet 2021 offer comprehensive sustainability insights [162]; yet they necessitate substantial datasets and considerable computational resources for precise projections [143]. Circularity Scoring System and Swave matrix applications facilitate the quantification of circularity and environmental repercussions [87]; but they rely on established procedures and data consistency across various industries [147]. The IoT-driven SC information architecture improves traceability and automation [151]; yet necessitates robust cybersecurity standards and compatibility among various systems [178]. Cloud-based manufacturing services provide scalability and cost-effectiveness [162]; yet they present hazards about data security, reliance on infrastructure along with elevated implementation expenses [178]. Big data analytics and computer modelling enhance decision-making and predictive maintenance; yet their efficacy relies on the acquisition of high-quality data and the implementation of appropriate processing methods [151].

The long advancement of digital transformation technologies will result in an intelligent, highly automated, and data-driven battery SC [145]. Advanced LCA and CE

methods will be comprehensively included into SC decision-making, guaranteeing sustainable material utilization and waste minimization [24]. IoT and cloud-based technologies will facilitate real-time SC transparency which allows for autonomous monitoring, automated compliance tracking, and adaptive production methods [151]. Big data analytics and computational modelling will enhance predictive algorithms, facilitating improved resource allocation, risk assessment, and process optimization [162]. As digital transformation progresses, the battery SC will evolve into a hyper-connected ecosystem, enhancing efficiency, sustainability, and resilience against disturbances [161].

3.2.2.8. Advanced technological innovation and infrastructure

Utilization of sophisticated technological advancements and infrastructure technological advancements and infrastructure are enhancing efficiency, precision, and sustainability in battery production, recycling, and SC management through the integration of intelligent planning models, digitalization, and automated resource recovery techniques [31]. Strategic insights and planning frameworks, like Pythagorean Fuzzy Analytic Hierarchy Process [151], Monte Carlo simulation [89], and Technique for Order Preference by Similarity to Ideal Solution [43], facilitate data-driven decision-making, risk evaluation, and optimization of material flows. Prospective dynamic macro material flow analysis improves long-term planning for battery resource allocation, guaranteeing sustainable and efficient material use [135]. Moreover, micro recycling methods and selective thermal transformation enable the recovery of high-purity materials while minimizing energy-intensive processing processes, hence enhancing the circularity and resource efficiency of the battery SC [149]. The implementation of digital systems and intelligent technologies is augmenting automation, connection, and real-time surveillance in battery infrastructure [119]. Industry 4.0 applications amalgamate cyber-physical systems, IoT-enabled monitoring, and AI-driven automation, enhancing industrial accuracy and efficiency [80]. Autonomous and connected vehicle technologies are enhancing logistics, improving transportation efficiency, and monitoring battery performance, hence minimizing SC delays and emissions [139]. The direct regeneration method for battery management facilitates real-time battery diagnostics and predictive maintenance, hence prolonging battery longevity and enhancing second-life applications [79].

Diverse technical breakthroughs and infrastructure models have distinct advantages and trade-offs regarding efficiency, automation, and implementation complexity [128]. Strategic planning models like Pythagorean Fuzzy Analytic Hierarchy Process and Monte Carlo methods

improve decision-making precision but necessitate extensive datasets and significant computer resources for optimization [89]. Micro recycling and selective thermal transformation enhance material recovery efficiency [93], although necessitate specialized processing infrastructure and advancements in scalability [11]. Industry 4.0 and digital smart technologies provide real-time tracking, automation, and SC flexibility [80]; yet they require substantial investment and robust cybersecurity measures to mitigate data vulnerabilities [178]. Autonomous and connected vehicle systems enhance transportation efficiency [133] but depend on infrastructure enhancements and sophisticated AI integration for complete implementation [183].

The long-term advancement of sophisticated technologies will revolutionize battery manufacturing, resource management, and the integration of the CE into a completely automated, AI-driven, and exceptionally efficient system [164]. AI-driven predictive analytics will further strengthen strategic planning models, facilitating proactive modifications in material flow and optimizing the SC [151]. Micro recycling and selective thermal transformation will standardize battery material recovery, reducing waste and energy usage [155]. Industry 4.0 and smart manufacturing applications will facilitate self-optimizing production facilities, thereby diminishing operational inefficiencies and emissions [96]. Autonomous mobility and AI-driven battery management will establish a linked, self-optimizing SC, guaranteeing optimal efficiency in battery consumption, logistics, and recycling [139]. These developments will transform the battery industry through the incorporation of intelligent, sustainable, and highly automated technologies, fostering long-term resilience and sustainability in energy storage and mobility sectors [169].

3.2.3. Global policy and regulations

This section addresses Objective 3 by examining the role of policy frameworks in shaping the sustainable trajectory of the EV battery SC. Table 4 outlines the key features of global policy and regulations, encompassing 7 policy types, 29 key policies, and 40 detailed policies (see Appendix D) from various countries. By investigating these key policies, this section aims to understand their influence on the development and implementation of sustainable practices within the complex EV battery ecosystem. The analysis highlights how different countries approach sustainability through regulatory frameworks, shaping both the current and future sustainability of the EV battery SC. These policies aims to minimize energy usage and reduce the carbon footprint that are associated with recycling of LIBs, enhancing sustainability and CE, initiatives for managing material and components along with vehicle to

grid integration regulations, adopting incentives and subsidies for EV, and laws for supporting the R&D innovation in the EV battery SC along with targets that emphasizes the responsibility to adhere human rights throughout the SC, improving includes in ensuring the battery traceability throughout the production [77,100, 169].

Table 4

Identification and classification of country-wise key policies for EV batteries.

Policy types	Key policies	Countries
(1) Environmental standards and regulations	(a) Regulatory frameworks for battery and recycling	EU, China, Japan, US, Germany, Global, Chile, Bolivia
	(b) Environmental sustainability and circular economy enhancement	EU, Global, China, US, Germany, Bolivia
	(c) Material and component management	EU, Global, China, DRC, Chile, Indonesia
	(d) Energy integration and vehicle-to-grid strategies	UK
(2) Incentives and subsidies	a) Incentives and subsidies for EV adoption and infrastructure development	Global, EU, US, China, UK, Pakistan, Brazil, Japan, India
	(b) CE and recycling initiatives	Global, EU, US, China, Denmark, India, Mexico
(3) SC transparency and due diligence	(a) SC due diligence and human rights	Global, Germany, China
	(b) Sustainability and transparency in battery production and recycling	EU, China, Mexico, Bolivia, Chile
	(c) Resource management and environmental impact	DRC
(4) Research and development funding	(a) Sustainable infrastructure and recycling innovations	Global, US, Japan, Canada, China
	(b) Support for electric vehicle battery SC	China, US
(5) End-of-life management regulations	(a) End-of-life management regulations and closed-loop recycling China, Global.	US, EU, Mexico
	(b) Battery recycling regulations and EPR policies	China, Global, US, EU, Japan, South Korea, Brazil, Switzerland, UK
	(c) Subsidy policies and incentive programs	China
	(d) New energy vehicle (NEV) battery recycling regulations	China
	(e) Recycling regulations and state-specific legislation	US
	(f) Zero waste goals and recycling mandates	US
	(g) Infrastructure investment and jobs act	US
	(h) EU battery directive and related regulations	EU
	(i) Reward-penalty mechanisms and recycling facilities support recycling legislation	EU, Japan, South Korea
	(j) Recycling laws and high collection rate achievement	Japan, Switzerland
	(k) Lack of specific legislation for libs	Brazil
(6) Emissions standards	(a) EV adoption and emissions limitations	EU, UK, US, Global
	(b) GHG emission regulations	UK, US
	(c) Carbon neutrality and emissions reduction initiatives	Global, China, EU, UK, US
	(a) Eco-design and life cycle standards for EV batteries	Global

Environmental standards and regulations refer to the rules and guidelines established to protect the environment by managing the impact of industrial processes and products. Regulatory frameworks for batteries and recycling are discussed in 29% of the articles, with countries such as China, the US, the EU, Mexico, Japan, Germany, Chile, and Bolivia participating in global efforts. Policies focused on environmental sustainability and CE enhancement are addressed in 18% of the literature, with key participants including the US, China, and the EU.

Material and component management policies are mentioned in 7% of the studies, with countries like Chile, Indonesia, China, the Democratic Republic of the Congo (DRC), and the EU taking part. Energy-integration and vehicle-to-grid strategies aimed at improving energy storage and stability are discussed in 2% of the papers, with the UK standing out for these initiatives.

Incentives and subsidies for promoting EV adoption and infrastructure development are referred to in 24% of the articles, supported by regions such as the Global community, EU, US, China, UK, Pakistan, Brazil, Japan, and India. Policies supporting CE initiatives and recycling are also discussed in 24% of the studies, with global efforts led by countries including the US, China, Denmark, India, Mexico, and the EU.

SC transparency and due diligence, with a focus on ethical and environmental regulations, are highlighted in 5% of the papers. These policies address SC due diligence and human rights issues enacted globally and in regions like Germany and China. Additionally, sustainability and transparency in battery production and recycling are practiced in the EU, China, Mexico, Bolivia, and Chile. Resource management and environmental impact policies, reviewed in 2% of the studies, are supported by the DRC.R&D funding, aimed at advancing new technology and innovation within the EV battery SC, is covered in 16% of the papers. Global efforts from countries such as the US, China, Japan, and Canada are key in driving these plans. Specific funding for the EV battery SC is discussed in 5% of the studies, with China and the US playing pivotal roles in supporting these initiatives.

EOL management regulations fortifies responsible disposal and recycling of products to minimize environmental impacts policies. The key policies encompass of EOL management regulations and closed loop are discussed in 14% of articles where China, Global, US, EU, Mexico supports this policy. Battery recycling rules EPR policies presented in 20% of the

studies. China, the US, the EU, Japan, Sweden, Brazil, Switzerland, South Korea and the UK are the nations concerned. In China's, subsidy policies and incentive programs and, new vehicle battery recycling regulations which are addressed in 9% and 10% papers, respectively. US has the recycling regulations and state specific legislation, zero waste goals and recycling mandates and, Infrastructures investments and jobs acts initiative, which is discussed in 4 %, 5%, 4% respectively. The EU battery directive and related laws, 15% of articles mention this initiative. 6% of the studies present reward-penalty mechanisms and recycling facilities and the act for resource recycling electrical and electronic equipment and vehicle implemented in the EU, Japan and South Korea. 5% of the paper present recycling laws and high collection rate achievement in Japan and Switzerland. Brazil highlights a lack of specific legislation for LIBs within the country where only one percentage of papers addresses this gap. This is due to the focus only on regions with key players in the battery and EV markets like US, China, the EU and Japan.

Emissions standards are laws to limit pollution from vehicles and industries to pursue reducing GHG emissions and alleviate to climate change. The initiatives like EV adoption and emissions limitations where 8% of papers mentioned and countries involved are the EU, the UK, the US, and various global. 1% of the papers address GHG emission regulations that are adopted by the UK and the US. Carbon neutrality and emissions reduction initiative are discussed in 3 % of articles and the countries involved are Global focus, China, EU, UK and the US. Product labelling and certifications assure that products encounter regulatory and quality standards, encouraging environmental compliance and sustainability. Eco-design and life cycle standards are mentioned only 3 % of articles where global initiatives are taken part. China has implemented certification of recycling enterprises that are discussed in 3% of studies.

Countries like China [34], the US [68], the EU [64], Germany [70], Bolivia [88], Chile [98], Indonesia [126], DRC [42] and globally have initiated environmental standards and regulation policies. Policies encouraging incentives and subsidies from the countries like Global [22], the EU [31], the US [128], China [64], the UK [68], Pakistan [147], Brazil [100], Japan [109], India [71], Mexico [65] and Denmark [80]. Countries like Global [22], EU [76], Germany [153], China [150], Mexico [65], Bolivia [47], Chile [70] and DRC [42] have initiated the policies related to SC transparency and due diligence. According to Kumar et al. [122], Cheng et al. [76], and Calienes et al. [133] stressed about the countries like US, China, Japan and Canada initiatives for research and developing incentives. While Castro et al. [100] emphasized the lack of specific policies legislation for LIBs.

Table 5 provides a detailed analysis of national policies regarding EV batteries in prominent nations, emphasizing quantitative factors such as policy coverage, enforcement intensity, and effectiveness assessments. The analysis encompasses essential domains, including climate objectives, infrastructure enhancement, manufacturing incentives, and recycling regulations, to illustrate how nations tackle the sustainability and technology problems associated with EV battery systems. Countries have established ambitious climate objectives to underpin their EV battery strategies, with legislative scope differing according to national priorities. China intends to attain carbon neutrality by 2060, emphasizing substantial investments and intelligent long-term planning in its programs [85]. The EU has established more aggressive objectives, aiming for carbon neutrality by 2050 and reduce emission by 55% by 2030 [186], along with carbon dioxide emissions regulations (measured in g CO₂ km⁻¹) will become more tighten with 37.5% reduction for cars and 31% reduction for vans between 2021 and 2030 [187]. The US aims for carbon-neutral power by 2035 and net emissions zero by 2050 [191], while Canada pursue net-zero emissions by 2050 and 100% EVs by 2030 [196], respectively. India's aim to attain 100 percent electric transportation by 2030 [200]. These aims serve as the foundational framework for further infrastructure investments, industry initiatives, and recycling legislation [200].

Infrastructure development is a crucial measure of the severity of policy enforcement, with each nation making substantial investments to facilitate EV battery uptake. By 2020, China has created over 120,000 charging stations and 4.8 million charging outlets [85], bolstered by the investment of RMB 90 million for further charging infrastructure under the 13th five-year plan [184]. Over 30 Chinese localities provide incentives for residential or public charges, underscoring localized implementation [184]. The EU aims to achieve its target of 30 million zero-emission vehicles by 2030 through stringent CO₂ rules and the enhancement of infrastructure [188]. The United States exhibits significant enforcement intensity by designating \$7.5 billion for the installation of 500,000 EV chargers across the nation by 2030 [192, 193]. Concurrently, Canada has allocated \$150 million over a three-year period for charging stations, so strengthening its policy objectives [197]. India's regulatory framework emphasizes the swiftly growing EV battery sector, anticipated to develop by \$300 billion from 2017 to 2030 [200]. These infrastructure advancements signify the gravity of enforcement across various places.

The strength of policy enforcement is significantly indicated by the financial and regulatory backing for battery manufacture. China imposes restrictions on subsidies, confining them to large-scale battery facilities with a minimum capacity of 8 GWh [185]. Tax concessions

enhance incentives for home firms, promoting global investments while safeguarding local industries [185]. The EU fosters local production via investments, exemplified by the EUR 480 million designated by the European Investment Bank for an LG Chem Gigafactory in Poland [189]. The US aims to decrease battery costs to \$60 per kWh by 2025 and reduce EV production expenses by 50% by 2030 [194]. Canada has invested CAD 590 million in Ford Motor company Canada to bolster local EV production, in addition to CAD 100 million for Lion Electric's battery assembly facility [198,199]. These specific incentives illustrate the correlation between enforcement rigor and technological advancement, enhancing the worldwide competitiveness of EV batteries.

Table 5

EV batteries policy comparison through quantitative indicators.

Countries	Policy coverage		Enforcement intensity	Effectiveness assessments
	Climate targets	Infrastructure developments	Manufacturing incentives	Recycling policies
China	-Achieve carbon neutrality by 2060 [85].	- Establishing over 120,000 stations for charging and exceeding 4.8 million power terminals in 2020 [85]. -The thirteenth Five-Year Strategy allocated RMB 90 million for the construction of charging stations [184]. -Over 30 cities offer subsidies for personal or commercial EV recharging [184].	-Limiting subsidies exclusively to large scale battery production plants with a minimum capacity of 8 GWh [185]. -Tax concessions for battery manufacturers [185]. - Restricting EV subsidies on cells manufactured in China for all worldwide investments [185].	- Promote for uniformity of cell manufacturing, design, validation, and refurbishment for second-life applications [186].
EU	-Attain carbon-neutral status before 2050 and a minimum 55% decrease in emissions by 2030 [186]. - Regulations on carbon dioxide emissions (estimated in g CO ₂ km ⁻¹) for automobiles are going to tighten by 37.5% and for vans by 31% from 2021 to 2030 [187].	-By 2030, a minimum of 30 million passenger zero-emission vehicles should be in circulation with nearly all passenger light duty vehicles and heavy commercial vehicles achieving zero emissions by 2050 [188].	- In early 2020, the European Investment Bank provided EUR 480 million to finance the building of a LG Chemistry batteries with lithium-ion cell-to-pack production Gigafactory in Poland [189].	- Commencing on July 1, 2024, both industrial and batteries for EVs are required to disclose their carbon impact for marketing purposes [190]. -Enhancing transparency in the cell sector and monitoring of massive battery packs across their life cycle through the use of modern information technologies, such as the battery passport [190].
US	- Achieving carbon-neutral energy by 2035 while attaining zero GHG emissions throughout the economic system by 2050 [191].	-Establishing a national infrastructure of 500000 EV chargers by 2030 [192]. - Allocate \$7.5 billion for the development of a nationwide infrastructure of EV stations [193].	-Formulate government initiatives to facilitate the development of robust domestic and international sources and supplies of essential substances by 2025 [194]. -Lower expenses to get a \$60 per kWh battery cost by 2025 [194]. -Eradicate Co and Ni in LIB by 2030 [194]. -By 2030, Reduce the cost of EV pack manufacturing by 50% [194].	- Promote the development of battery packs to improve their reusability and recyclability by 2025 [195]. - By 2025, enhance recuperation rates for essential elements including lithium, cobalt, nickel and graphite [195]. - Implement incentives to achieve a 90 percent recycling rate for commercial electronics, EVs, and grid-storage cells around 2050 [195].
Canada	- Achieve zero net emissions by 2050 [196].	- Allocate a further \$150 million across a three-year span for the development of refuelling and charging facilities throughout Canada, as declared in 2020 [197].	-Allocating CAD 590 million to Ford Motor Company Canada to enhance EV production [198]. - Quebec and federal ministries are allocating CAD 100 million to Lion Electric to aid in the establishment of a cell module production facility [199].	- Lithion Recycling Inc. generated \$3.8 million, whilst Li-Cycle Corp. obtained \$2.7 million for batteries with lithium-ion recycling [85].
India	- The Indian government aims to achieve completely EVs by 2030 [200].	- The country's battery market will continue to expand by \$300 billion from 2017 to 2030 [200].		
Japan				-The 2000 Japanese law concerning the promotion of effective resource utilization concerns LIB [201].

Recycling and second-life uses are essential metrics for evaluating the efficacy of sustainability-oriented programs. China advocates for the standardization of battery design, production, validation, and refurbishment to facilitate efficient second life uses and enhance resource recovery [186]. The EU mandates that rechargeable EV batteries declare their carbon impact beginning in 2024 and promote lifecycle openness via its battery passport project, which improves market traceability [190]. The United States aims to enhance recovery rates of essential elements, including lithium, cobalt, nickel, and graphite, by 2025, with a long-term objective of attaining a 90% recycling rate for consumer electronics and EV batteries by 2050 [195].

Canada's investments in Lithion Recycling Inc. and Li-Cycle Corp. underscore its dedication to effective battery waste management and material reclamation [85]. Japan's 2000 laws emphasis on efficient resource management guarantees enduring sustainability via established recycling protocols [201]. These recycling programs illustrate how nations reconcile environmental objectives with the security of material supply [126]. This study's result provides potential future opportunities for development of SCSC for EV batteries. The EU and China dominate position with highest policy and regulations, this is due to their intense environmental goals, market management, technological innovations, implemented policies for resource control, and combined CE strategies [109]. Country like India, also an advancing nation with less policies have been developed. As a developing country. India can have a potential for massive EV markets due to its vast population. So, the developed countries can collaborate project that focused on battery technologies. Attracting foreign direct investment from Chinese and European companies.

4. Integrating sustainability within circular supply chain

This section aims to address the main RQ of integrating the sustainability impacts within the EV battery SC. By developing a conceptual framework to explore Environmental, economic, social, and governance (EESG) impacts. This framework ensures to fulfil the comprehensive objective of combining all the strategies across different stages of SC that provide a holistic perspective and can enhance sustainability.

4.1. Sustainability impacts

Figure 6 provides a comprehensive classification of sustainable impacts, organized into four primary categories, 16 sub impacts and 64 detailed sustainable impacts(objective 4). Each of these impacts encompasses key elements that are interconnected and crucial for a holistic understanding of sustainability. For instance, environmental sustainability impacts focus on preserving biodiversity and ecosystems, which are essential for a SCSC for EV battery. This includes restoring environments post-mining and integrating climate adaptation strategies such as implementing carbon offset programs and investing in renewable energy sources. These actions help minimize ecological disruptions and ensure that the SC not only reduces its carbon footprint but also contributes positively to environmental protection, as supported by studies like Niri et al. [21], Yang et al. [85], and Sarkar et al. [63].

For economic sustainability impacts, ensuring long-term cost-effectiveness is crucial for the SCSC of EV batteries. By implementing resilient strategies such as market diversification and investing in emerging technologies, the SC can better adapt to global economic changes. These actions help foster economic stability and growth, safeguarding the SC from market volatility. This approach aligns with the findings of studies like Gebhardt et al. [28], Wang et al. [43], Reuter [49], and Kumar et al. [112] which emphasized the importance of economic resilience and proactive investment in sustaining the EV battery SC

Within an SCSC for EV batteries, addressing social equity and fair resource distribution ensures that local communities benefit equitably from economic activities. Establishing strong labour standards and ensuring safe working conditions throughout the SC, while supporting human rights and improving community health, are critical. These social impacts also foster trust and support from stakeholders, as highlighted by studies such as Mota et al. [51], Tang et al. [98] and Petavratzi et al. [152].

Lastly, robust governance and accountability are essential for a SCSC in EV battery. Integrating sustainability into industrial practices and enforcing policies that ensure transparency, straightforward reporting, and stakeholder participation strengthens ethical standards. By upholding policies that ensure sustainability commitments throughout the SC, the industry can maintain high governance standards, as supported by studies Das et al. [30], Tavana et al. [151] along with Wei and Dou [159]. This approach ensures long-term sustainability and ethical practices within the EV battery SC.

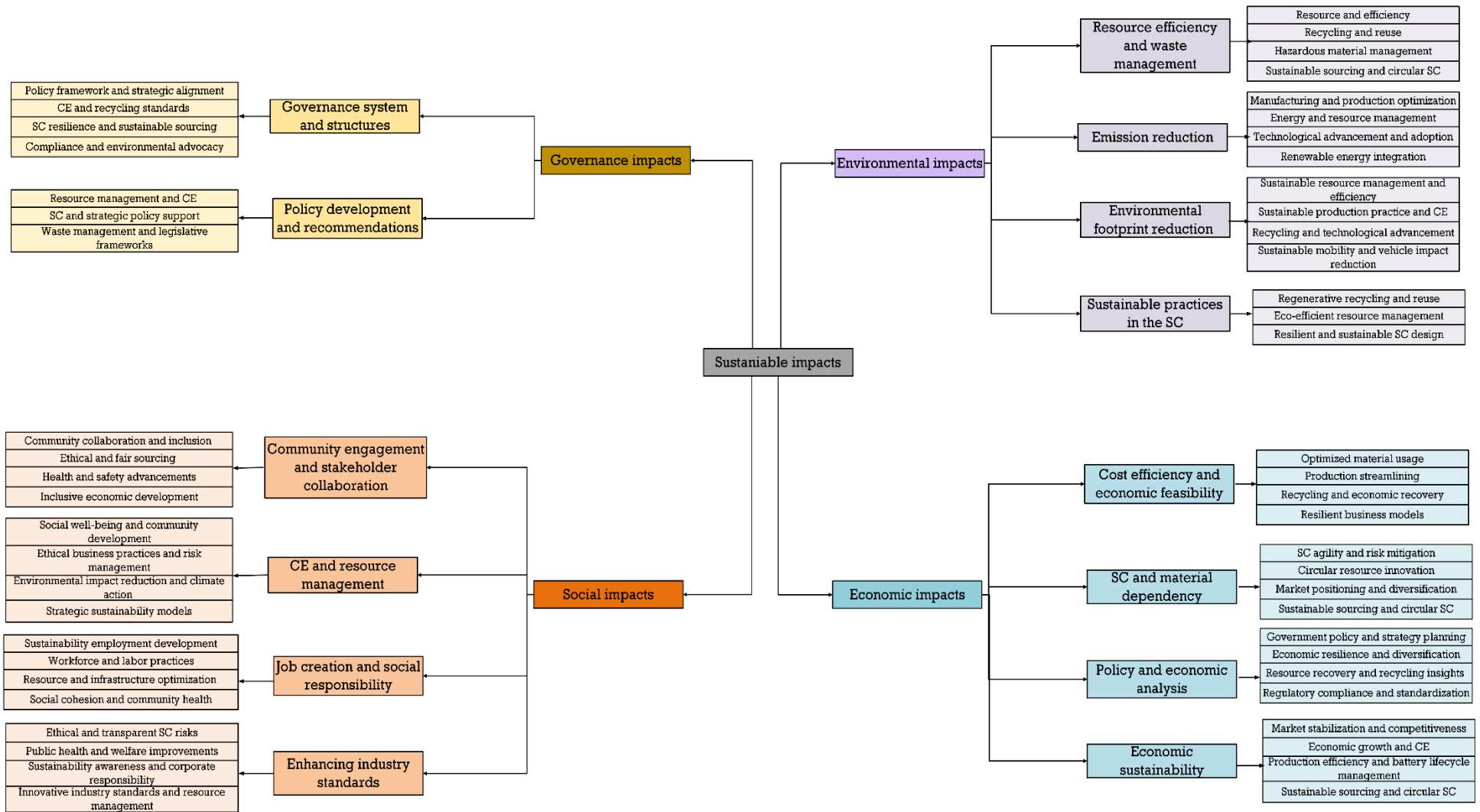


Fig. 6. Comprehensive classification of sustainable impact.

4.2. Conceptual framework

Figure 7 depicts a synthesis of the study's findings. From this, we develop a framework that offers a comprehensive overview of research in the field of SCSC for EV battery. Detailing from mining stages to recycling phase, the challenges (CH), their solutions (SL), technologies (T) used to address these challenges, and the policies and regulations (PR) that are carried out to support these solutions. EESG impacts are examined for each stage. Thus, highlighting the innovative technologies and effective policies can contribute for advancing sustainability in EV battery SC.

With this framework, the mining stage have significant environmental impacts and sustainability challenges (CH1) like CHS1 and CHD2 (see Appendix A where CHS1 is sub challenges and CHD1 is detailed challenges). To address these issues, the sector can implement resource efficiency and CE practices (SL1), along with deploying technological solutions that align with governmental standards aimed at minimizing environmental damage and recycling and material processing technologies (T1) such as TS1 and TD1 (see Appendix C where TS1 is sub technologies and TD1 is detailed technologies) are used to ensure sustainable mining by applying environmental standards and regulations (PR1) policies like, PRK1, and PRD1(see Appendix D, where PRK1 are key policies and PRD1 are description of key policies). This approach enhances environmental sustainability such as by reducing habitat destruction and pollution, fostering sustainable economic impacts, improving social factors, and promoting strong governance across global mining operations. Through these combined efforts, the SCSC for EV batteries can advance toward achieving long-term sustainability goals.

In the processing, refining, and manufacturing stage, the primary challenge is achieving resource efficiency and incorporating alternative materials (CH6). Solutions for this include CE models, advanced material technologies, resource optimization strategies, and sustainable design principles (SL6), all driven by recycling and material processing technologies (T1). Incentives and subsidies (PR2) play a crucial role in encouraging the adoption of these technologies, leading to significant EESG sustainability impacts by reducing waste, minimizing energy consumption, and shaping effective policies to address these challenges.

At the supplier stage, the focus shifts to enhancing SC and economic resilience (CH2). Solutions here involve strategic SC optimization, sustainable material sourcing, CE practices, fostering collaborative partnerships, providing incentives, and increasing organizational capacity and production efficiency (SL2). SC innovations (T3) are supported by policies

promoting SC transparency and due diligence (PR3), which collectively improve EESG sustainability while building more resilient and sustainable supply networks.

In the battery assembly phase, the focus is on tackling industrial process efficiency (CH10) through optimizing production processes, utilizing sustainable materials and battery technologies, enhancing SC and network efficiency, and adopting sustainable recycling practices (SL10). Automation and robotics (T4) play a key role in improving efficiency and minimizing waste, while R&D funding (PR4) supports these technological advancements. This results in a significant EESG impact by optimizing resource utilization and minimizing industrial waste.

In the integration of batteries into EVs, the primary challenge is overcoming technological innovation and infrastructure barriers (CH4). Solutions include implementing CE and sustainable practices, intelligent technologies, digital transformation, material and infrastructure innovation, and strategic modelling and market analysis (SL4). Technologies (T5) such as product labelling and certifications (PR5) ensure these practices promote EESG sustainability.

During the distribution to end-users, challenges related to digital transformation for sustainability (CH7) are addressed through strategic insights, decision models, smart analytics, optimization technologies, life cycle analysis, and digital tracking solutions such as blockchain (SL7). Eco-friendly technologies (T6) help reduce the environmental footprint, while environmental standards and regulations (PR1) ensure sustainable distribution practices, collectively achieving substantial EESG sustainability impacts.

In the EOL stage, challenges related to the policy and regulatory framework (CH5) are central. Solutions include the implementation of regulatory standards and compliance, incentives, market strategies, CE policies, resource efficiency, and environmental impact reduction (SL5). These efforts are supported by advancements in battery technologies (T7) designed for recycling and reuse. EOL management regulations (PR6) ensure that disposal and recycling practices are conducted sustainably, resulting in significant EESG sustainability impacts.

The collection of used batteries faces challenges linked to social and legal implications (CH9). Collaborative policy and standards, public awareness initiatives, education, compliance, fair practices, and transparency (SL9) are key solutions. Digital transformation technologies (T8) further enhance efficiency and transparency in the collection process. Emission standards (PR7) help regulate these practices, contributing to EESG sustainability by ensuring responsible and ethical collection methods.

In the recycling process phase, challenges in recycling and material management (CH3) are tackled through circular production practices, resource efficiency, innovative recycling technologies, strategic policy frameworks, and infrastructure development (SL3). Recycling and material processing technologies (T1) play a critical role in optimizing resource recovery, supported by environmental regulations (PR1) that ensure EESG sustainability through reduced landfill usage and efficient material recovery.

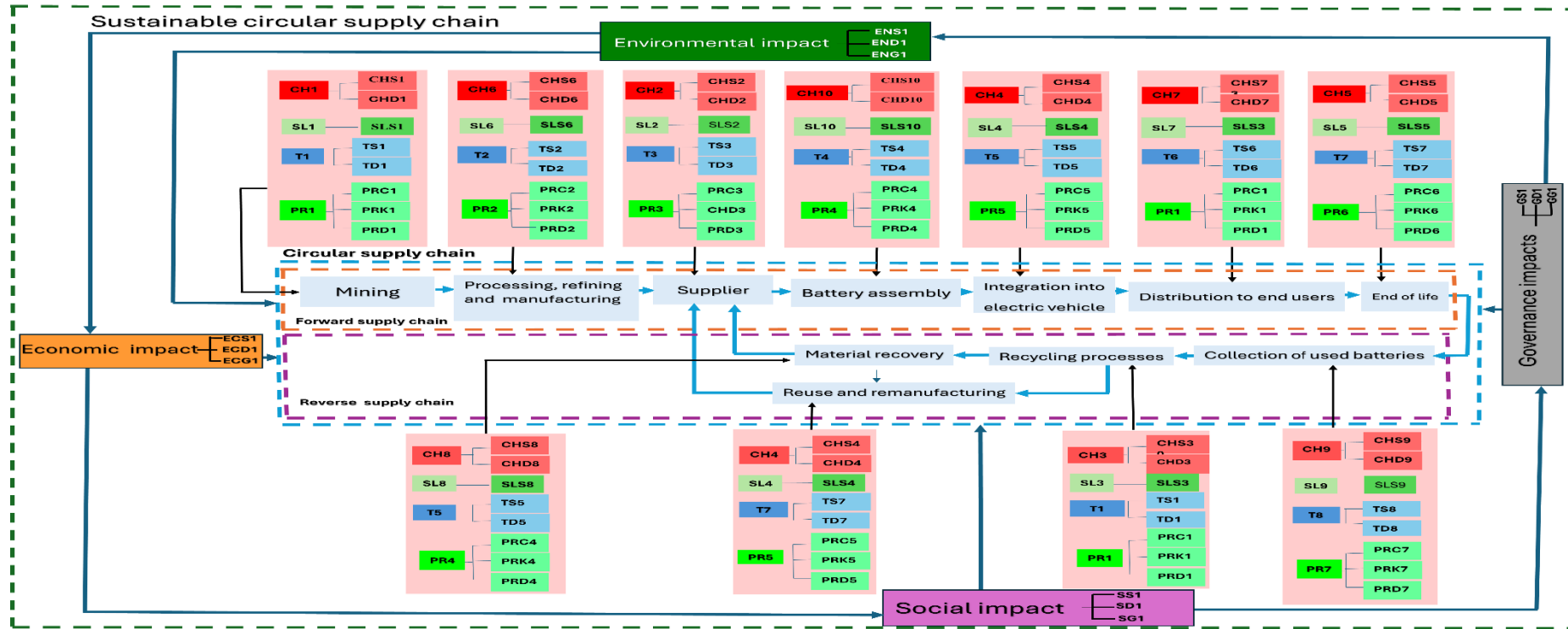


Fig. 7. Conceptual framework for sustainable circular SC for EV batteries.

Note: CH1: Environmental and sustainability challenges. CH2: SC and economic resilience. CH3: Recycling and material management. CH4: Technological innovation and infrastructure. CH5: Policy and regulatory framework. CH6: Resource efficient and alternative materials. CH7: Digital transformation for sustainability. CH8: Research and systematic analysis. CH9: Social and legal implications. CH10: Industrial process efficiency.

S1: Resource efficiency and circular practices, technological solutions for sustainability, policy guidelines to minimize environment, sustainability manufacturing and energy. S2: Strategic SC optimization, sustainable materials and CE, collaborative partnerships and incentives, organizational capacity and production efficiency. S3: Circular production and resource efficiency, innovative recycling technologies and methods, strategic policy and collaboration framework, design, diagnostic, and infrastructure. S4: CE and sustainable practices, intelligent technologies and digital transformation, technological innovation in materials and infrastructure, strategic modelling and market analysis. S5: Regulatory standards and compliance, incentives and market strategies, CE policies and sustainable, resource efficiency and environmental impact reduction. S6: CE models, advanced material technologies, resource optimization strategies, sustainable design principles. S7: Strategic insights and decision models, smart analytics and optimization technologies, mapping and life cycle analytical tools, blockchain and digital tracking solutions. S8: Research methodologies and analysis tools, innovation and advanced technologies, strategic planning and SC management, incentives and policy approaches. S9: collaborative policy and standards, public awareness and education, compliance and fair practices, transparency and social well-being. S10: Production process optimization, sustainable material and battery technologies, SC and network efficiency, sustainable and recycling practices.

T1: Recycling and material processing. T2: Automation and robotics. T3: SC innovation. T4: Automation and robotics. T5: Advanced sorting and classification. T6: Eco-friendly technologies. T7: Battery technologies. T8: Digital transformation.

PR1: Environmental standards and regulations. PR2: Incentives and subsidies. PR3: SC transparency and due diligence. PR4: R&D funding. PR5: Product labelling and certifications. PR6: End-of-life management regulations. PR7: Emissions standards.

The material recovery stage addresses challenges in research and systematic analysis (CH8). Solutions include adopting research methodologies, advanced technologies, strategic planning, and SC management (SL8). These efforts are supported by R&D funding (PR4), leading to EESG sustainability through efficient material recovery and minimized waste.

In the reuse and remanufacturing stage, challenges related to technological innovation and infrastructure (CH4) are mitigated by implementing CE practices, intelligent technologies, and digital transformation (SL4). Adaptable battery technologies (T7) are essential for reuse, while product labeling and certifications (PR5) ensure that these practices extend product life cycles and reduce resource demand, ultimately enhancing EESG sustainability.

5. Theoretical, practical implications, and policy recommendations

Building upon the conceptual framework, this section outlines the theoretical, practical, and policy implications that can guide the future development of sustainable SCSC for EV batteries.

5.1. Theoretical and practical implications

This research creates a strong foundation by creating a comprehensive conceptual framework that incorporates sustainability throughout the lifecycle of EV batteries inside the circular SC. This foundation is strong as it incorporates and modifies established ideas and approaches from other disciplines, providing a systematic framework for future study and actual implementations. Since 2019, there has been a significant rise in academic and industrial interest in SCSC for EV batteries, reflecting global efforts to combat climate change and prioritize sustainable solutions in the EV sector. The study highlights interdisciplinary approaches, integrating knowledge from various journals and publications to address the multifaceted challenges of sustainability in SCs. It also emphasizes the importance of intellectual and collaborative leadership in enhancing scientific collaboration and knowledge distribution. Intellectual leadership denotes the initiation of new theoretical advancements, whereas collaborative leadership highlighting the cooperative endeavors among academia, industry along with policymakers to effectively apply these theories, thereby improving scientific collaboration and knowledge dissemination across sectors.

However, the increased interest in SCSC has also led to notable challenges. The results of this research provide a basis for further exploration of advanced solutions and can expand

theoretical investigations into the application of CE practices in the EV battery SC. The study identifies crucial gaps in current regulatory frameworks and policy implementations, offering insights that can be used to develop new theories and policy recommendations aligned with sustainable practices. Academically, this work can guide research toward promising areas for technological innovation, particularly advanced recycling technologies and alternative battery chemistries, which are vital for promoting sustainability in EV battery SCs.

This research highlights the essential requirement to amalgamate insights from environmental science, economics and engineering, promoting a multidisciplinary strategy that substantially enhances sustainable practices throughout the SC for EV batteries. The report offers pragmatic strategies that might sufficiently improve the sustainability of EV battery SCs. Implementing CE standards aligns with global sustainability objectives, optimizes operations, and enhances the adoption of breakthrough recycling technology.

Moreover, the use of sophisticated technologies like big data, IoT, and blockchain significantly improves SC transparency and operational efficiency. These technical incorporations allow industry professionals to enhance traceability, markedly decrease waste, and attain exceptional sustainability results. The research delineates concrete techniques such as urban mining for essential metals, investments in renewable energy, and strategic facility location, thereby ensuring that theoretical findings are effectively converted into practical applications. These apps possess the capacity to establish new industry benchmarks and impact practices, offering a definitive route to attaining improved sustainability results, as demonstrated by heightened resource efficiency and mitigate environmental impact in pilot projects. This research underscores the essential importance of public awareness and education in fostering responsible consumer behavior and enhancing involvement in recycling initiatives. Targeted educational efforts and public engagement programs enlighten customers on the lifecycle impacts of EV batteries and the advantages of recycling, which can substantially affect their purchasing decisions and disposal practices. These strategies aim to increase engagement and support for SCSC in the EV battery sector. The study emphasizes the importance of collaborative endeavors among many stakeholders which include industry leaders, governmental entities, and academic institutions.

Through collaboration, these entities may formulate and execute cohesive and efficient strategies for managing EV battery SCs, ensuring that all stakeholders contribute to and endorse the transition towards more sustainable consumer habits and recycling practices. This technique not only improves consumer awareness but also actively engages them in the sustainability process by fostering a more informed and involved public that endorses CE

projects. Expanding on these fundamental collaborative and educational strategies, this study further examines the incorporation of advanced technologies and complicated modeling methods that substantially improve the theoretical frameworks of SC management for EV batteries.

Innovative technologies, including direct and specialized recycling methods, advanced network design, and eco-friendly technologies, enrich the extended theoretical framework by demonstrating the benefits of various recycling and material processing techniques. The use of advanced models like Stackelberg game theory, and multi-layer network models deepens the understanding of SC optimization and network dynamics by emphasizing their network dynamics and applications across various literatures. Furthermore, this evaluation underscores that new research leveraging advanced sorting systems and intelligent classification techniques, powered by AI and machine learning, provides essential insights for improving material recovery and operating efficiency. These technological breakthroughs expand the range of SC sustainability concerns while presenting refined and adaptable models for analysis and simulation, equipping industry practitioners and policymakers with essential tools to simulate and anticipate outcomes with greater precision. Through the aggregation and synthesis of these findings from the literatures, the research broadens the theoretical framework of SCSC and introduces an enhanced model for practical implementation, paving the way for future research to investigate and incorporate these latest technologies and methodologies. The technical insights require a thorough evaluation of current policy frameworks to ensure they adequately facilitate the adoption and use of sophisticated technologies in the global SC [11, 49].

Practically, the study is beneficial to manufacturers, legislators, and recycling companies. Manufacturers can implement efficient recycling techniques and sophisticated sorting technology to improve sustainability and cost-efficiency. Policymakers can utilize the study's findings to formulate enhanced resource recovery regulations and optimize operational efficiency throughout the EV battery SC. The research provides a comprehensive analysis of how various regulatory frameworks influence battery management and recycling practices by systematically comparing and assessing policies across regions based on criteria such as resource recovery rates, regulatory compliance, and incentives for recycling efficiency. This contrast, articulated through the assessment of significant policies in Appendix D, underscores certain domains where policies demonstrate strengths or encounter constraints.

The analysis of policy interactions, technology, and sustainability enhances the theoretical framework of SCSC, providing a guide for future scholarly investigation into policy

efficacy, regulatory effects, and the incorporation of global standards. Policymakers, industry stakeholders, and recycling organizations can leverage these data to enhance battery lifecycle management. The study assesses the recycling targets of the European Green Deal, the influence of California's carbon fuel limits on sustainable energy consumption, and the impact of China's end-of-life management regulations on material recovery efficiency. These assessments offer practical recommendations for enhancing sustainability in EV battery SCs. Policymakers can formulate more efficacious regulations and incentives that foster recycling and sustainability, while industry practitioners can synchronize their operations with worldwide standards, optimize compliance, and augment sustainability.

The findings on sustainability impacts lay the groundwork for further academic research and innovation in theoretical models related to SCSC for EV batteries. By analysing EESG impacts, the research significantly contributes to the academic discourse on sustainability. It highlights critical areas such as resource efficiency, cost-effectiveness, economic feasibility, and community collaboration elements that are essential for developing robust theoretical frameworks. The results can be used to conduct detailed governance analyses and make recommendations for improving SCSC, influencing both governmental and organizational policies in support of the Sustainable Development Goals.

Experts in the EV battery industry can apply these insights to optimize their SCs, improve resource efficiency, manage waste, and minimize environmental footprints. Corporate entities can develop and implement sustainability plans that not only enhance their competitive advantage but also align with market demands for sustainable standards. Policymakers can utilize the detailed impacts presented in the study to design regulations and standards that support SCSC for EV battery. Finally, by recognizing the social sustainability impacts, organizations can strengthen relationships with communities and stakeholders, fostering enhanced social value and engagement.

5.2. Policy recommendations

To establish a SCSC for EV batteries, an integrated approach that addresses all aspects of the SC is essential. Each challenge requires coordinated efforts from specific stakeholders, guided by well-defined policy recommendations to ensure comprehensive progress in sustainability and efficiency. Table 6 presents policy recommendations for various stakeholders, along with essential suggestions for driving the advancement of a sustainable EV battery SC.

Table 6

Policy recommendations.

Challenges	Stakeholders	Policy recommendations	Implementation Strategies	Evaluation criteria
Environmental impact and sustainability	Governments, regulatory agencies, Industry, research institutions.	<ul style="list-style-type: none"> •Mandate lifecycle assessment for all EV batteries to identify environmental hotspots. •Impose carbon taxes on battery production and use to incentivize low-carbon alternatives. •Establish regulations for water usage and waste 	<ul style="list-style-type: none"> •Develop Life cycle assessment guidelines, mandate preapproval studies, establish results. •Tiered carbon tax by emissions, tax credits for low-carbon manufacturing. •Industry-specific water and waste standards enforce non-compliance penalties. 	<ul style="list-style-type: none"> •CO₂ emissions, water consumption, soil contamination, energy usage, material efficiency •GHG emissions, Carbon intensity, energy source type, production cost •Water consumption, chemical discharge, disposal efficiency, environmental compliance
Supply chain and economic resilience	Governments, industry, research institutions, industry.	<ul style="list-style-type: none"> •Provide tax incentives for domestic battery production and recycling. •Foster public-private partnerships for battery SC development. •Implement trade policies to protect domestic battery industry. 	<ul style="list-style-type: none"> •Tax intensive for investments. •Form SC consortiums, joint ventures. •Impose imports tariffs, export incentives. 	<ul style="list-style-type: none"> •Recycling facilities count, recovery rate, economic impact, government expenditure. •SC resilience investments, infrastructure development, partnerships count. •Import/export balance, domestic capacity, market competitiveness, trade dependency
Recycling and material management	Governments, industry, recycling companies, research institutions.	<ul style="list-style-type: none"> •Establish collection and recycling targets for battery components. •Support R&D of advanced recycling technologies. •Develop standards for traceability of battery material. 	<ul style="list-style-type: none"> •Mandatory recycling quotas, deposit-refund systems. •R&D grants for recycling, pilot new recycling methods. •Mandate digital tracking, require material sourcing reports. 	<ul style="list-style-type: none"> •Collection rate, recycling efficiency, landfill waste reduction, CE impact. •Technology adoption, recycling efficiency, cost reduction, hazardous waste reduction. •SC transparency, digital tracking, compliance rate, ethical sourcing.
Innovative technology and infrastructure	Governments, private sectors, industry, research institutions.	<ul style="list-style-type: none"> •Provide government funding for battery technology and R&D. •Establish battery testing and certification standards. •Support the development of second-life applications for EV batteries. 	<ul style="list-style-type: none"> •Launch grant, establish innovation hubs for EV battery technology. •Develop certification programs, mandatory safety testing. •Incentivize batteries reuse, partner energy storage repurposing. 	<ul style="list-style-type: none"> •Patents filed, innovation rate, funding utilization, industry adoption. •safety compliance, battery durability, failure rates, certification adherence. •Second-life applications, market penetration, energy storage, cost savings.
Policy and regulatory framework	Governments, international organizations, industry.	<ul style="list-style-type: none"> •Develop a comprehensive national battery strategy. •Create a level playing field for domestic and international battery manufacturers. •Promote international cooperation on battery standards and regulations. 	<ul style="list-style-type: none"> •Form strategy task force, align policies with global goals. •Implement fair competition policies, adjust tariffs balance. •Engage in global battery treaties, participate in regulatory forums. 	<ul style="list-style-type: none"> •Policy alignment, regulatory coverage, stakeholder participation, implementation rate. •Fair competition, market distribution, trade balance, industry collaboration. •Agreements, standardization, trade harmonization, and global impact.
Resource-efficient and alternative materials	Governments, research institutions, industry.	<ul style="list-style-type: none"> •Support R&D of alternative battery materials. •Implement resource efficiency standards for battery production. •Encourage the use of recycled materials in battery manufacturing. 	<ul style="list-style-type: none"> •Fund battery R&D, promote material collaboration. •Set efficiency benchmarks, mandate material efficiency reporting. •Subsidize recycled inputs, set procurement guidelines. 	<ul style="list-style-type: none"> •Mineral dependency, material efficiency, toxicity reduction, resilience. •Energy efficiency, material efficiency, waste minimization, green standard compliance. •Recycled material, CE contribution, waste reduction, cost savings.

		<ul style="list-style-type: none"> •Develop policies to secure critical material mineral SCs. 	<ul style="list-style-type: none"> •Ensure resource security policies, boost mineral investments. 	<ul style="list-style-type: none"> •Domestic sourcing , impots dependency, reserves, price stability.
Digital transformation for sustainability	Governments, industry.	<ul style="list-style-type: none"> •Invest in digital technologies for battery lifecycle management. •Develop data standards for battery information sharing. •Encourage the use of blockchain technologies for SC transparency. 	<ul style="list-style-type: none"> •Grants for tracking tools, open-source platforms. •data-sharing protocols, performance reporting. •Blockchain frameworks, decentralized traceability systems. 	<ul style="list-style-type: none"> •SC transparency, blockchain adoption, efficiency, data-sharing. •Adoption rate, data security, interoperability, real-time tracking. •Traceability, fraud reduction, compliance, digital adoption index.
Research and systematic	Governments, research institutions, industry.	<ul style="list-style-type: none"> •Increase public funding for battery related research. •Establish research collaboration between academia, industry, and government. •Foster knowledge transfer and technology commercialization. 	<ul style="list-style-type: none"> •Allocate research funds, promote collaborations. •Joint research programs, knowledge-sharing platforms. •Innovation hubs, Promote technology transfer deals. 	<ul style="list-style-type: none"> •Research output, collaboration, funding efficiency, breakthroughs. •Partnerships count, knowledge transfer efficiency. •Joint projects, policy impact.
Social and legal implications	Governments, industry, labor unions, communities	<ul style="list-style-type: none"> •Implement worker safety regulations in battery production facilities. •Develop community engagement plans for battery-related projects. •Establish liability frameworks for battery-related accidents. 	<ul style="list-style-type: none"> •Require regular safety inspections. •Enforce penalties. •Community consultations, stakeholder feedback •Strict liability laws compensation funds. 	<ul style="list-style-type: none"> •Injury rate, hazard compliance, training, well-being index. •Public participation, community impact, social acceptance, transparency index. •Legal cases, accountability, compensation, compliance rate.
Industrial process efficiency	Governments, industry, research institutions,	<ul style="list-style-type: none"> •Encourage the use of renewable energy in battery production. •Promote industrial symbiosis and resource sharing. •Implement waste minimization strategies in battery manufacturing. 	<ul style="list-style-type: none"> •Incentivize renewable manufacturing and mandate efficiency. •Promote resource sharing, establish partnerships •Zero-waste policies promote CE principles. 	<ul style="list-style-type: none"> •Renewable share, carbon reduction, industry efficiency, cost savings. •Resource efficiency, waste exchange, collaboration, CE impact. •Waste reduction, recycling efficiency, CE compliance, cost savings.

To mitigate the environmental impact of EV batteries, governments and regulatory bodies should require LCA to pinpoint environmental hotspots and enhance sustainability. Establishing a tiered carbon tax system can incentivize firms to embrace low-carbon options, while stringent rules on water consumption and waste disposal can guarantee responsible resource management. Penalties for non-compliance will encourage adherence to these standards, thereby diminishing carbon emissions, water pollution, and overall environmental degradation.

Establishing a robust EV battery SC necessitates diminishing reliance on foreign materials and augmenting indigenous production capabilities. Governments ought to offer tax advantages for domestic battery production and recycling, while promoting public-private partnerships to stimulate investment in infrastructure. Trade policies, including tariffs and export incentives, can enhance the protection of home industry. These actions will fortify the SC, guaranteeing stability and economic expansion in the EV battery market.

Improving battery recycling rates is essential for sustainability and resource efficiency. Governments ought to implement compulsory collection and recycling objectives, enforce deposit-refund mechanisms, and offer incentives for consumers to return used batteries. Advancing R&D in sophisticated recycling technologies can enhance efficiency and lower expenses, while digital tracking systems will promote transparency and guarantee ethical sourcing. These methods will foster a CE by reducing landfill trash and enhancing material recovery.

Investment in cutting-edge battery technologies and infrastructure is crucial for industrial progress. Governments and the corporate sector should finance R&D projects, implement national testing and certification standards, and advocate for second-life usage of EV batteries. Establishing research hubs and implementing safety regulations would propel technological advancement, enhance battery efficiency, and boost adoption rates, so assuring long-term sustainability in the EV sector.

An organized regulatory framework is essential to guarantee equitable competition, sustainability, and adherence in the EV battery industry. Governments ought to formulate a national battery strategy that aligns with global sustainability goals, implement legislation to ensure equitable conditions for both domestic and international manufacturers, and foster international collaboration on battery regulations. Efficient policy execution will bolster market stability, promote investment, and facilitate global trade harmonization.

Ensuring sustainable and efficient battery materials necessitates investigation into alternate chemistries and prudent resource management. Governments and industry leaders

ought to endorse R&D for novel battery materials, establish efficiency standards, and advocate for the utilization of recycled resources in battery manufacturing. Fortifying regulations to ensure crucial material SCs will diminish reliance on limited resources and improve long-term sustainability, thereby fostering a more robust battery sector.

Utilizing digital technologies can improve transparency and efficiency throughout the battery SC. Governments and industry stakeholders ought to invest in digital tracking technologies, implement global data-sharing protocols, and advocate for blockchain use to enhance SC transparency. These solutions will augment traceability, bolster adherence to sustainability requirements, and mitigate fraud, ultimately guaranteeing a more efficient and accountable battery lifespan.

Enhancing battery technology and sustainability necessitates robust collaboration among academia, industry, and government. Augmenting public financing for battery research, promoting university-industry collaborations, and creating knowledge-sharing platforms will stimulate innovation. These regulations will expedite progress in battery chemistry, recycling methods, and lifetime management by fostering systematic research and the commercialization of innovative technology.

Ensuring ethical and legal compliance in the EV battery sector necessitates the protection of worker rights and the involvement of local communities. Governments and industries must implement worker safety standards, require regular inspections, and create liability frameworks for battery-related incidents. Executing stakeholder discussions and transparency initiatives will enhance community engagement and social endorsement while guaranteeing accountability for environmental and social repercussions.

Enhancing industrial procedures in battery manufacture will diminish environmental impact and lower production expenses. Governments ought to advocate for renewable energy utilization, foster industrial symbiosis, and implement waste reduction methods. Promoting energy-efficient production and zero-waste practices can augment sustainability, boost resource efficiency, and facilitate the transition to a CE in battery manufacturing.

6. Conclusion, limitations and future work

The motivation for adopting a SCSC for EV batteries is driven by the need to mitigate climate change and prevent the transfer of environmental burdens. This study utilizes systematic analysis following the PRISMA methodology to identify, categorize, and address the challenges in establishing a SCSC for EV batteries. The research focuses on proposing and

evaluating effective solutions and technologies while also assessing the impact of relevant policies.

The study successfully achieves its objectives, identifying 10 main difficulties, 31 sub-challenges, and 160 detailed challenges within the EV battery SC. Challenges are ranked from least to most significant, facilitating a systematic prioritization of essential topics. Furthermore, solutions are categorized into short-term and long-term methods, differentiating urgent interventions from sustainable solutions that facilitate enduring enhancements. These challenges led to the formulation of 40 main solutions, 174 complete solutions, and the implementation of 102 detailed technologies, 24 sub-technologies, and 8 core technologies. These efforts contribute to significant progress in resource efficiency and technological integration. This research additionally investigates advanced technologies that facilitate circular supply networks. A comparison examination elucidates their advantages and weaknesses within each area, extending beyond their current application. Furthermore, a long-term impact assessment examines their scalability, cost-effectiveness, and contribution to sustainability objectives. Moreover, the analysis of policy are categorized into 7 policy types and examines 27 key policies from various regions reveal how diverse regulatory frameworks can either facilitate or impede sustainable practices. Policies are evaluated according to their coverage, enforcement rigor, and overall effect on sustainability and resource efficiency. These ideas form a conceptual framework that amalgamates challenges, solutions, and innovations to facilitate the transition to a circular and resilient EV battery SC. The resulting frameworks provide a strategic approach for improving environmental sustainability and economic resilience within the industry.

Despite its extensive reach, has certain drawbacks. It depends on English-language articles from 2009 to 2024 obtained from Scopus and Web of Science, perhaps excluding pertinent studies in other languages or earlier publications. Future study ought to integrate multilingual sources and historical analyses to encompass a wider array of perspectives. The study, while concentrating on EV battery SCs, may yield insights applicable to other sectors. An interdisciplinary examination of circular SC techniques may corroborate and enhance these findings. This study largely focuses on LIBs neglecting other battery technologies. Future research should examine alternate battery chemistries, including solid-state and sodium-ion batteries, to offer a more thorough understanding of sustainable battery SCs. Ultimately, integrating real-world decision-making elements and performing empirical case studies will enhance the practical relevance of these findings. Pilot projects and industry-led trials may provide significant insights into the viability and execution of proposed techniques.

This research provides a systematic framework for enhancing the sustainability of EV battery SCs, incorporating technology innovations, regulatory policies, and industry approaches. By tackling critical difficulties, suggesting specific answers, and examining global policy trends, it establishes a thorough basis for future research and industry advancement. Cooperation among politicians, industry executives, and researchers will be crucial for advancing a sustainable and robust EV battery SC.

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