Reverse Logistics for Lithium-Ion Batteries within the Circular Economy: A Systematic Literature Review from the Perspective of Industrial Sustainability

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Abstract: This systematic literature review examines the environmental impact of implementing reverse logistics networks for the recycling of lithium-ion batteries within the industrial sector. The research question was structured using the PIOC method (Problem, Intervention, Outcome, Context), and the PRISMA 2020 protocol was applied to ensure methodological rigor in the selection of studies. The literature search was conducted in the Scopus database, yielding 24 peer-reviewed articles that met all inclusion criteria. The results highlight substantial environmental benefits associated with reverse logistics, particularly in reducing CO_2 emissions, minimizing hazardous waste, and recovering critical raw materials. However, several recurring challenges were identified, such as the lack of regulatory frameworks, insufficient infrastructure for battery collection and treatment, and limited stakeholder coordination. The study concludes that reverse logistics plays a pivotal role in achieving a sustainable circular economy in the battery industry. Nonetheless, its effective implementation requires stronger public policies, financial incentives, and integrated strategies involving manufacturers, recyclers, and government institutions.

Keywords: Lithium-ion batteries, Reverse logistics, Environmental impact, Industrial sustainability.

I. Introduction

Over the past decade, the global transition toward electric mobility has significantly increased the demand for lithium-ion batteries, particularly within the automotive sector [1,2]. While this shift contributes to reducing greenhouse gas emissions from transportation, it also introduces a series of emerging environmental, economic, and social challenges related to end-of-life battery management [3,4].

To address this challenge, the circular economy framework advocates for strategies focused on the recovery, reuse, and recycling of resources, aiming to minimize waste and extend product lifecycles. Within this paradigm, reverse logistics (RL) plays a central role by enabling the efficient return of post-consumer products to appropriate recovery or controlled end-of-life processing systems [7-9].

In the specific case of lithium-ion batteries, numerous studies have demonstrated that the implementation of RL networks contributes significantly to reducing greenhouse gas (GHG) emissions, closing material loops, and mitigating environmental impacts across the battery lifecycle [10–12]. By facilitating the collection, transportation, and reintegration of used batteries into recycling or second-life applications, RL systems not only support resource efficiency but also enhance the overall sustainability of the electric mobility supply chain.

Despite the demonstrated potential of RL in battery recovery systems, their widespread adoption continues to face several critical barriers. Among the most significant challenges are the lack of targeted public policies, the absence of specialized infrastructure for collection and treatment, and the high operational costs associated with RL networks [13–16]. Furthermore, the effectiveness of existing solutions varies greatly depending on the region, the level of technological development, and the regulatory framework in place [17–19].

In response to these challenges, the academic literature has proposed a variety of optimization and strategic planning models aimed at improving the efficiency and feasibility of RL systems. These include facility location analysis, circular supply chain design, and multi-objective approaches that seek to simultaneously maximize environmental benefits and economic viability in battery recycling processes [20–22]. However, substantial knowledge gaps remain regarding the most effective strategies, the critical success factors, and the measurable environmental and industrial impacts of these initiatives when implemented in real-world scenarios [23–25].

Given these complexities, the present study aims to conduct a systematic literature review to assess the environmental impact of RL networks for lithium-ion battery recycling in the industrial sector. The review also seeks to identify the main barriers to implementation, the management strategies adopted across various contexts, and the key determinants of successful deployment framed within the broader goals of sustainable industrial development and the transition to a circular economy.

The main contributions of this study are: (i) to systematically identify institutional, logistical, and economic barriers that limit the implementation of RL in lithium-ion battery recycling; (ii) to classify and compare the main management strategies adopted in different industrial contexts; and (iii) to highlight the critical success factors that enable the articulation of policies, infrastructure, and stakeholder participation for a more effective circular economy.

The article is organized as follows: Section II describes the methodology applied, Section III presents the results of the review, Section IV offers the critical discussion, and Section V provides the conclusions and recommendations, including proposals for future research.

II. Methodology

This systematic literature review, which follows a qualitative-descriptive approach without performing a meta-analysis, was designed to examine recent research focused on the implementation of RL networks for lithium-ion battery recycling in industrial settings. The study adheres to the

PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), a well-established and widely adopted protocol used in high-rigor scientific investigations [4,19].

To construct the research question and define the inclusion and search criteria, the PIOC model (Problem, Intervention, Outcome, Context) was applied. This framework enables the systematic breakdown of a research problem into its core elements, ensuring a more targeted, relevant, and coherent literature search process [5,17]. Based on this model, the central Research Question (RQ) guiding this review was formulated as follows:

The central Research Question (RQ) guiding this review was formulated as follows:

RQ: *How does the implementation of RL networks for lithium-ion batteries affect environmental impact reduction within the context of industrial companies?*

In alignment with the components of the PIOC model, the following sub-research questions were also defined to structure the analysis:

RQ1: What are the main barriers faced by industrial companies in the recycling of lithium-ion batteries?

RQ2: What management strategies have been employed to implement RL systems for battery recycling?

RQ3: What outcomes have been reported in terms of environmental impact reduction following the implementation of such systems?

RQ4: What specific factors influence the effectiveness of lithium-ion battery recycling in the industrial sector?

Table I. PIOC Components and Corresponding Keywords Used in the Systematic Search

Component	Description	Key339words
P – Problem	Recycling lithium-ion batteries	*lithium*, *lithium-ion batteries*, *battery recycling*, *electric batteries*, *battery*
I– Intervention	Implementation of a reverse logistics network	*logistics*, *reverse logistics*, *supply chains*, *circular economy*, *reverse logistics network*
O– Outcome	Environmental impact of lithium batteries	*sustainable development*, *waste management*, *electronic waste*, *environmental impact*, *optimization*
C – Context	Industrial companies and facilities	*companies*, *manufacturing*, *manufacturers*, *industry*, *facilities*

The literature search was conducted using the Scopus database, selected for its high level of indexing, multidisciplinary scope, and recognized academic reliability. To ensure alignment with the PIOC model, keywords were defined in English for each component Problem, Intervention, Outcome, and Context allowing the construction of a robust and well-structured search equation tailored to the review's objectives. The final selection included studies published between 2020 and 2025, in English or Spanish, that met the established inclusion criteria.

In addition, a targeted search for scientific literature was conducted using the **Scopus** database, recognized for its extensive multidisciplinary coverage and high indexing standards. Based on the keywords identified in **Table I**, the following Boolean search equation was formulated to retrieve relevant publications:

(lithium OR "lithium-ion batteries" OR "battery recycling" OR "electric batteries" OR "battery") AND (logistics OR "reverse logistics" OR "supply chains" OR "circular economy" OR "reverse logistics network") AND ("sustainable development" OR "waste management" OR "electronic waste" OR "environmental impact" OR "optimization") AND ("companies" OR "manufacturing" OR "manufacturers" OR "industry" OR "facilities")

This search strategy was designed to capture studies that intersected all components of the PIOC model—problem, intervention, outcome, and context—ensuring alignment with the systematic review's objectives.

To refine the scope of the review and ensure the relevance and quality of the selected literature, a rigorous set of inclusion and exclusion criteria was applied during the screening process. The **inclusion criteria (IC)** were as follows:

IC1. Studies must explicitly address the recycling of lithium-ion batteries.

IC2. The research must describe or apply methodologies related to RL in the context of battery recycling.

IC3. Articles must report results that demonstrate the effectiveness of implementing RL networks or strategies.

IC4. The studies must be conducted in industrial or business contexts involving lithium battery recycling processes.

Additionally, the following **exclusion criteria (EC)** were established:

EC1. Studies focusing on sectors outside the industrial or manufacturing domains.

EC2. Documents that are not peer-reviewed scientific publications (e.g., theses, textbooks, technical reports, or non-indexed material). Peer-reviewed conference papers were accepted.

EC3. Publications written in languages other than English or Spanish.

EC4. Articles published prior to the year 2020.

Once the inclusion and exclusion criteria were clearly defined and aligned with the objectives of this systematic review, the bibliographic search was conducted using the Scopus database, chosen for its academic prestige, interdisciplinary breadth, and high indexing quality. The Boolean search equation, developed based on the PIOC model, initially returned a total of **856 scientific articles**.

To ensure a **systematic, reproducible, and transparent selection process**, the study followed the **PRISMA 2020** protocol (*Preferred Reporting Items for Systematic Reviews* *and Meta-Analyses*) [4], [19], widely recognized as a best practice in evidence-based literature synthesis.

During the **identification stage**, no duplicate records were detected, as the search was limited to a single, comprehensive database (Scopus). In the **screening stage**, the titles, abstracts, and keywords of all 856 retrieved articles were carefully reviewed. This initial assessment led to the exclusion of **734 papers** that were not thematically aligned with the research scope, resulting in **122 studies** deemed eligible for full-text evaluation.

In the **eligibility stage**, full-text versions of the selected articles were sought. However, **47 papers** were excluded at this point due to restricted access, as they were not available through open access platforms and could not be retrieved via institutional subscriptions.

Subsequently, the **remaining 75 articles** were subjected to a thorough analysis based on the previously established exclusion criteria:

18 articles were excluded for not being conducted in industrial or manufacturing contexts (**EC1**),

14 articles were excluded for not being original peer-reviewed scientific works (**EC2**),

0 articles were excluded due to language restrictions (**EC3**),

18 articles were excluded for being published prior to 2020 (**EC4**).

It is important to note that some documents met more than one exclusion criterion; therefore, the totals may include overlapping cases.

Ultimately, after rigorously applying all stages of the PRISMA protocol, **25 scientific articles** were selected. These publications fully meet the methodological rigor, thematic relevance, and quality standards required for inclusion and constitute the final **corpus of analysis** for this systematic review.

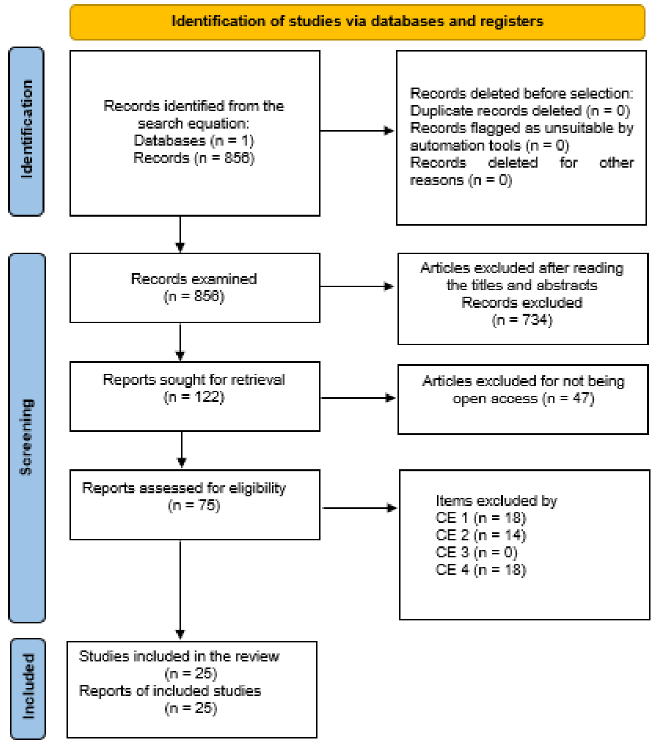

Fig. 1. PRISMA Flow Diagram

Identificación

- **Records identified through Scopus** (n = 856)

Cribado

- **Records after title/abstract screening** (n = 122)
- **Excluded after screening** (n = 734)

Elegibilidad

- **Full-text articles assessed for eligibility** (n = 75)
- **Excluded:**
  Not accessible (n = 47)
  EC1: Not industrial/manufacturing (n = 18)
  EC2: Not original scientific work (n = 14)
  EC3: Language (n = 0)
  EC4: Published before 2020 (n = 18)

Inclusión

- **Studies included in final review** (n = 25)

III. RESULTS

RQ1: What are the main barriers faced by industrial companies in the recycling of lithium-ion batteries?

The analysis of the selected literature reveals a set of recurring barriers that hinder the effective implementation of RL networks for lithium-ion battery recycling. These obstacles can be categorized into three main dimensions, each of which significantly impacts the efficiency, scalability, and feasibility of such systems:

- **Institutional and Regulatory Barriers:** These include the lack of specific legislation for end-of-life battery management, inconsistent regulatory frameworks across countries or regions, and the absence of fiscal incentives, subsidies, or extended producer responsibility (EPR) schemes to encourage private-sector participation in recycling activities [6, 8,13,24]. Such regulatory gaps limit the establishment of a supportive policy environment needed to scale RL operations.

- **Logistical and Technological Barriers:** These refer to the underdevelopment or complete absence of efficient collection systems, limited infrastructure for battery sorting and transportation, and difficulties in tracking battery units throughout their lifecycle. The lack of standardized labeling and digital traceability tools further complicates the monitoring and recovery of LIBs from diverse sources, including electric vehicles, consumer electronics, and industrial equipment [3,14,19].
- **Economic and Organizational Barriers:** These challenges include high operating and transportation costs, limited access to private investment or financing, and the inherently low profitability of traditional LIB recycling schemes particularly in the absence of scalable technologies or economies of scale. Furthermore, the volatility of secondary material markets (e.g., lithium, cobalt) often deters sustained industrial engagement [11, 18, 20].

Together, these limitations affect both the technical feasibility and economic sustainability of RL networks tailored for lithium battery recycling. Addressing them requires coordinated efforts from policymakers, manufacturers, and technology developers to create enabling conditions for circular value chains.

Fig. 2 summarizes the main barriers identified across the reviewed studies, organized according to their frequency of appearance in the literature and grouped by category.

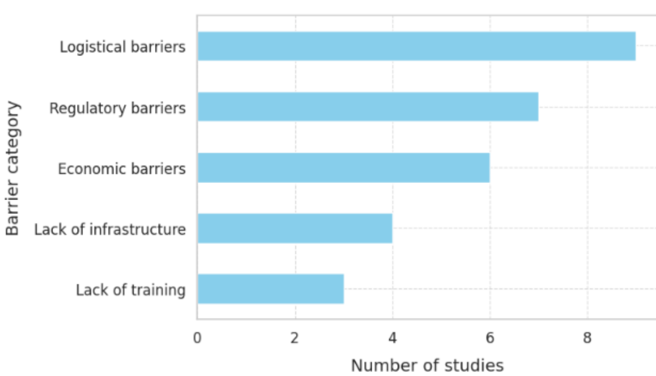

Fig 2. Barriers vs. Number of Articles

RQ2: What management strategies have been used to implement RL systems for lithium battery recycling?

The most frequently applied strategies in the reviewed studies are centered around **logistics optimization models**, with particular emphasis on the following approaches:

- **Optimal facility location** (treatment plants, collection and recycling centers), used to reduce transportation costs and carbon emissions [2,6,10,19].
- **Reverse logistics network design** using linear, integer, or fuzzy programming models to ensure operational efficiency in the recovery of critical materials [3,12,15].
- **Collaboration among supply chain stakeholders** (manufacturers, logistics operators, recyclers) through integrated management models, local government involvement, and digital platforms for traceability [9,16,22].
- **Life Cycle Assessment (LCA)** as a support tool for strategic decision-making in system design [7,25].

These strategies aim not only to improve economic efficiency but also to align with environmental policies and sustainability principles.

Figure 3 illustrates the most used management strategies across the reviewed studies, highlighting a clear preference for optimal facility location models and interorganizational collaborative approaches.

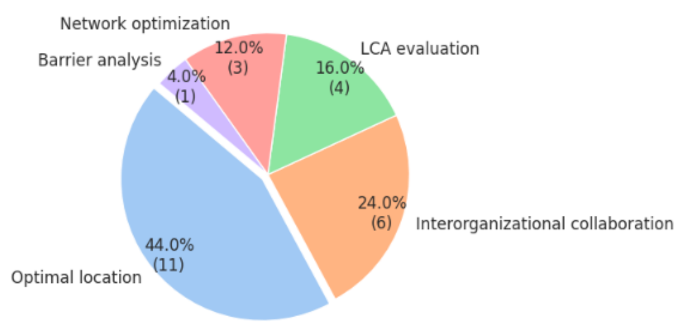

Fig. 3 Management Strategies

RQ3: What environmental impact reductions are observed following the implementation of RL systems for lithium battery recycling?

The 25 articles analyzed consistently report that the implementation of RL networks for lithium battery recycling significantly contributes to multiple positive environmental outcomes:

- **Reduction of greenhouse gas (GHG) emissions**, particularly carbon dioxide (CO_2), resulting from decreased demand for raw material extraction and optimized transportation logistics [1,5,17,21].
- **Decreased volume of hazardous waste**, through the recovery of valuable and potentially toxic materials such as lithium, cobalt, and nickel. This recovery reduces the environmental burden associated with landfilling and uncontrolled disposal [4,10,23].
- **Increased energy efficiency across the supply chain**, made possible by structured return flows and consolidated logistics systems that lower energy consumption and operational redundancies [14,19].

- **Alignment with the United Nations Sustainable Development Goals (SDGs)**, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), highlighting the broader socio-environmental relevance of RL for battery recycling [6,7,25].

Fig. 4 illustrates the most reported environmental benefits across the studies reviewed, with CO_2 and GHG emission reductions emerging as the most frequently cited outcomes.

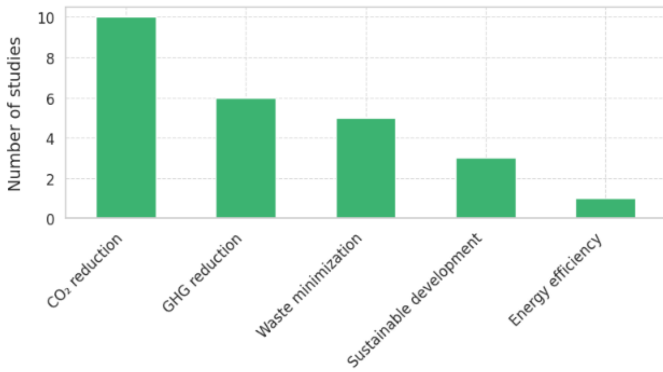

Fig. 4 Environmental Outcomes – Number of Studies

RQ4: What Specific Factors Influence the Effectiveness of Lithium Battery Recycling Systems?
The analysis of the selected studies revealed eleven key factors that significantly influence the effectiveness of lithium battery recycling systems in industrial settings. Among these, the most frequently cited include:

- **Availability of Specialized Infrastructure and Treatment Technologies:** The presence of technologically advanced facilities directly impacts the quality and safety of the recycling process, enabling the recovery of valuable materials and minimizing environmental risks [3, 8, 20].
- **Design of Efficient Logistic Networks:** Particularly those utilizing multi-objective optimization models or geospatial approaches, which improve routing, reduce costs, and enhance system responsiveness [2, 6, 12].
- **Institutional Support and Public Policy:** Including fiscal incentives, regulatory frameworks, and extended producer responsibility (EPR) schemes that facilitate systemic adoption and accountability across the value chain [4], [16], [18].
- **Technical Workforce Training:** Skilled personnel are essential for ensuring the safe handling of hazardous materials and the effective operation of recycling processes, thus impacting overall system efficiency [14], [24].
- **Consumer Participation and Environmental Awareness:** Active engagement from end users improves return rates of spent batteries and fosters a culture of sustainability, which is essential for closing the materials loop [9], [11].

While many of these factors are addressed individually across different studies, at least three—**institutional support**, **adequate infrastructure**, and **logistical system design** appear consistently across the literature, suggesting that they have a critical influence on the success of battery recycling systems.

Fig. 5 presents a summary of the most frequently cited critical success factors, highlighting the central role of institutional backing, robust infrastructure, and strategic network design in the effectiveness of RL systems for lithium battery recycling.

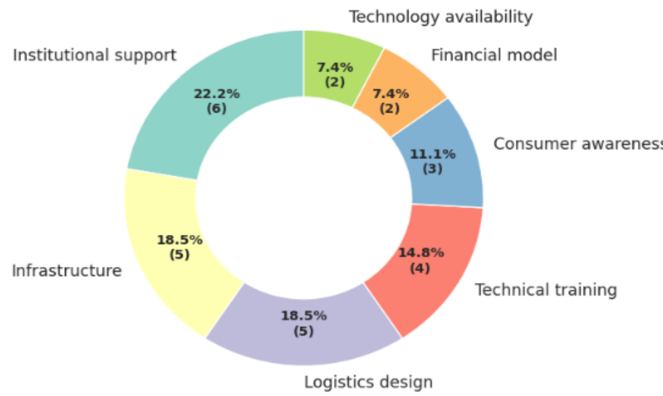

Fig. 5 Factors – Number of Studies

IV. DISCUSSION

The findings of this study confirm that the implementation of RL networks for lithium battery recycling constitutes a viable and necessary strategy for advancing toward more sustainable industrial models. In particular, the reduction of pollutant emissions, the recovery of critical materials, and transportation optimization represent well-documented environmental benefits in the literature [1, 6, 11, 23].

However, this process is not without limitations. The institutional and logistical barriers identified in RQ1 highlight a persistent gap between technological advancements and the development of public policies that support their adoption in the industrial sector. Several studies report that the absence of consistent regulatory frameworks and the low level of investment in specialized logistics infrastructure remain critical obstacles [3,8,18].

Regarding RQ2, although the most frequently applied strategy involves the optimal location of recycling facilities [2, 5,10], other approaches—such as inter-organizational collaboration and reverse network optimization through mathematical programming demonstrate high potential for replication and scalability, particularly in urban or regional contexts with high waste generation density [9, 14, 22].

As for RQ3, empirical evidence shows positive environmental impacts associated with RL models, with estimated reductions in CO_2, GHG emissions, and hazardous waste [4,7,12]. These findings suggest that the benefits go beyond economic efficiency, positioning RL as a practical tool to advance the Sustainable Development Goals, especially those related to responsible production (SDG 12) and climate action (SDG 13) [6, 25].

Finally, the results related to RQ4 confirm that the effectiveness of recycling systems depends on multiple factors, particularly government support, adequate logistics infrastructure, and efficient design of collection and processing networks [13,17,20]. Additionally, although less frequently discussed, technical staff training, the financial model adopted, and the level of public participation also influence system performance [15, 21, 24].

Taken together, these findings reveal that the success of RL systems does not rely solely on operational decisions, but rather on a multi-scalar articulation that integrates strategic planning, institutional commitment, and environmental governance.

It is also important to highlight the role of international institutions and standardization bodies. Organizations such as ISO, IEC, and SAE, as well as agencies responsible for patents, regulations, and environmental standards, play a central role in consolidating technical frameworks that enable interoperability and safety in battery recycling systems. Without their active participation, technological advances in RL may fail to achieve large-scale and globally consistent adoption.

Furthermore, while this review focused on lithium-ion batteries, several of the findings are applicable to other recycling sectors. The need for robust regulatory frameworks, optimized facility location models, and citizen participation can also be extrapolated to the recycling of other electronic waste streams, such as lead-acid batteries or consumer electronics. This suggests that RL represents not only a pathway for the battery industry but also a scalable model for broader circular economy practices.

A. DISCUSSION – CRITICAL ESSAY

This systematic review highlights the strategic role of RL in the transition toward a circular economy in the lithium battery sector. Based on the rigorous analysis of 25 scientific studies, significant progress has been identified, yet structural limitations, emerging challenges, and gaps in the literature still demand attention.

One of the most robust findings is the confirmation that RL systems significantly reduce greenhouse gas (GHG) emissions, recover critical materials, and optimize logistics flows. These benefits go beyond environmental gains—they also offer improvements in energy security by decreasing dependence on primary mining for lithium, cobalt, or nickel. However, this potential remains constrained by institutional, logistical, and economic barriers, revealing a disconnect between technological development and structural conditions for implementation.

Evidence shows that institutional barriers, especially the absence of clear policies, incentives, and harmonized regulations, are as critical as technological constraints. Most studies agree that without solid regulatory frameworks, technological innovations are unlikely to scale within industrial contexts. In this regard, the implementation of **Extended Producer Responsibility (EPR)** schemes stands out as a key tool, yet their adoption remains incipient, particularly in the Global South.

Another important point is that the prevailing strategies in the literature such as optimal facility location or mathematical optimization models show a clear technical orientation but overlook social or institutional aspects. This suggests that a gap persists between quantitative approaches and a holistic understanding of the socio-technical systems where RL operates. There is a lack of studies that integrate collaborative governance models, citizen participation, or environmental justice as relevant variables in system design.

It is also necessary to highlight that few studies analyze the unequal impact of recycling infrastructure in regions with varying development levels. Most of the reviewed articles originate from industrialized countries, which limits the applicability of these models in emerging economies, where informal electronic waste management and weak institutional capacity are structural factors. This omission represents an important **epistemological limitation** in the current body of literature.

An emerging topic with significant potential is the integration of disruptive technologies such as artificial intelligence, blockchain, and digital twins to enhance traceability, efficiency, and transparency in RL chains. While still marginal in the reviewed studies, this trend should be considered a priority research line moving forward.

Regarding the **methodological limitations** of this study, although the review relied on a single database (Scopus) chosen for its quality and interdisciplinary coverage, this choice may have restricted the inclusion of relevant articles from other sources, especially case studies or research in Spanish published in regional databases like Scielo or Redalyc. Furthermore, limiting the analysis to publications from 2020 onwards, while appropriate to capture recent trends, may have excluded valuable earlier contributions.

Among the main future challenges is the need to consolidate hybrid models that combine quantitative approaches with institutional and social perspectives, recognizing the complex and multidimensional nature of recycling networks. It will also be essential to foster international cooperation to share best practices, harmonize technical standards, and promote supranational legal frameworks, particularly in the context of global trade in electronic waste.

Ultimately, RL systems for lithium batteries represent a powerful tool, but their effectiveness depends on the articulation of technology, public policy, social engagement, and environmental governance. Progress in this direction will not only contribute to a more sustainable industry but also to a more just, resilient future aligned with global sustainability goals.

IV. CONCLUSIONS

This systematic literature review has provided an integrated analysis of the environmental impact of implementing RL networks for lithium battery recycling within the industrial sector. Based on the review of 25 scientific articles, the following conclusions can be drawn:

- RL is a key tool within the framework of the circular economy, as it enables the recovery of valuable materials, reduces pollutant emissions, and minimizes hazardous waste resulting from the widespread use of lithium-ion batteries [3], [6], [11].
- The most effective strategies include the optimal design of logistics networks, strategic placement of recycling facilities, and collaboration between public and private stakeholders. These approaches have been shown to improve both operational efficiency and environmental outcomes [2], [5], [14].
- The most frequently reported barriers are institutional, economic, and technical in nature. Notable obstacles include the lack of specific regulations, high operational costs, and insufficient infrastructure for the collection, sorting, and processing of used batteries [8], [13], [18].
- The effectiveness of RL systems depends on multiple factors, including institutional support, technological availability, human resource training, regulatory frameworks, and consumer engagement. The coordinated articulation of these elements is essential to ensure the sustainability of recycling networks [15], [17], [20].

Based on these findings, the following recommendations are proposed:

- Promote integrated public policies that include economic incentives, clear regulatory frameworks, and extended producer responsibility (EPR) schemes to foster the adoption of sustainable models in the industrial sector [4, 16].
- Encourage investment in specialized infrastructure, with a focus on clean technologies and regionally distributed treatment centers, to support material loop closure in alignment with circular economy principles [6,9].
- Strengthen institutional and human capacities by implementing technical training programs, fostering intersectoral partnerships, and developing digital traceability platforms to ensure transparency and efficiency in logistics operations [7], [21].
- Deepen applied research—particularly in the context of emerging economies to adapt RL models to diverse geographic, economic, and regulatory realities.

As lines of future research, it is suggested to: (i) explore the integration of emerging technologies such as artificial intelligence, blockchain, and digital twins to improve traceability and efficiency in RL chains; (ii) conduct comparative analyses of policies and regulatory standards between industrialized and emerging economies; and (iii) evaluate the applicability of RL models to other strategic waste streams, such as electronic waste and lead-acid batteries, within the broader framework of the circular economy.

In conclusion, the development of RL systems for lithium battery recycling is not only technically feasible, but also essential for advancing toward sustainable and resilient industrial models aligned with global environmental sustainability goals.

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