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# Recycling and Reinforcement of Retired EV Battery Materials in Polymer Composites for Sustainable Engineering Applications

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## *Abstract*

*The rapid proliferation of electric vehicles (EVs) has led to a substantial increase in lithium-ion battery waste, necessitating sustainable strategies for material recovery and reuse. This review explores the valorization of retired Electrical Vehicle batteries within polymer and composite systems, highlighting second-life applications as a promising pathway toward circular material utilization. Batteries retaining 70–80% of their original capacity remain suitable for extended use; however, beyond conventional energy storage, their constituent materials—including electrode powders, current collectors, and separators—can be effectively incorporated into polymer matrix composites for both functional and structural applications. This study critically examines battery degradation mechanisms, material recovery processes, and the transformation of recovered components into composite fillers and reinforcements. Particular emphasis is placed on polymer–battery material interactions, processing techniques such as melt blending and solution casting, and the resulting mechanical, electrical, and thermal properties of the developed composites. Techno-economic analysis demonstrates the feasibility of cost-effective material substitution, while life cycle assessment highlights significant environmental benefits, including reduced carbon footprint and conservation of critical raw materials. Emerging strategies, including hybrid composite systems, conductive polymers, and multifunctional materials, are discussed alongside key challenges such as material heterogeneity, interfacial compatibility, and large-scale scalability.*

*Finally, This strategy not only mitigates the environmental burden associated with battery waste but also promotes resource circularity by converting end-of-life materials into value-added functional components. the integration of retired EV battery materials into polymer composites represents a novel and high-impact approach, advancing sustainable materials engineering and efficient energy resource management for future technologies*

**Keywords:** Recycling, Reinforcement, Polymer Composites, Sustainable Engineering

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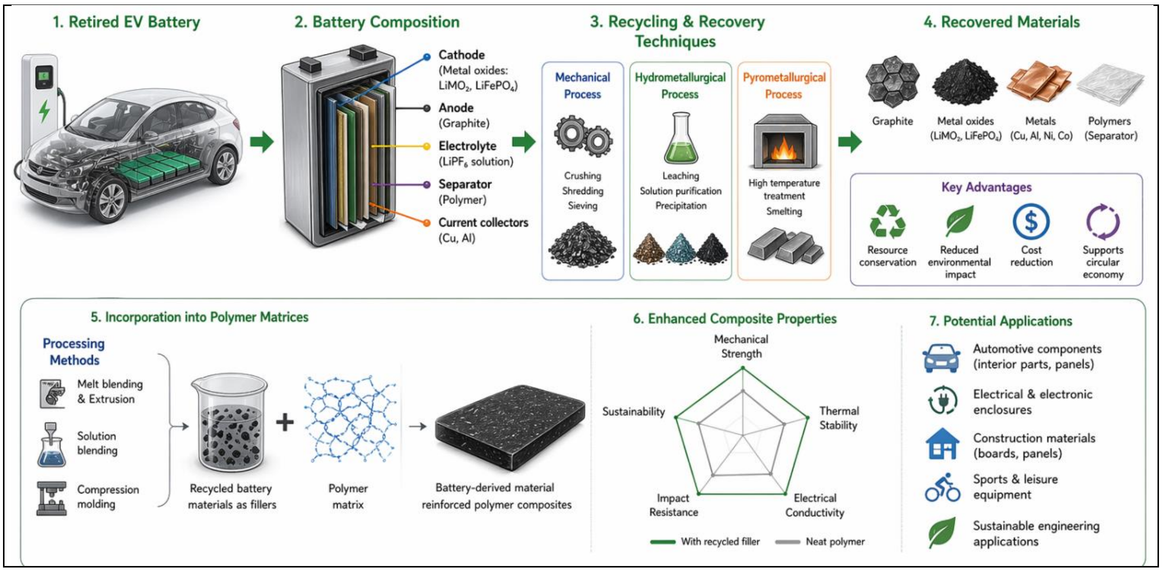
## GRAPHICAL ABSTRACT



## INTRODUCTION

The global transition toward electrified transportation has accelerated significantly, leading to a rapid increase in electric vehicle (EV) adoption and, consequently, lithium-ion battery production [1]. According to the International Energy Agency [2], EV battery demand is expected to grow more than fourfold by 2030 compared to 2023 levels, intensifying concerns regarding the sustainable management of end-of-life batteries [3]. While EV batteries are typically retired when their state-of-health (SOH) declines to 70–80%, they still retain substantial functional and material value [4]. Traditionally, second-life applications have focused on stationary energy storage; however, emerging research highlights the potential of these retired batteries as secondary raw materials for advanced polymer and composite systems. The concept of second-life battery utilization has evolved beyond energy applications toward materials valorization, where components such as cathode/anode powders, metallic current collectors, and polymeric separators are repurposed as functional fillers or reinforcements in polymer matrices [5-7]. This approach not only extends the lifecycle of battery materials but also aligns with circular economy principles by reducing dependency on virgin resources and minimizing environmental impact.

From a materials science perspective, the integration of recycled EV battery constituents into polymer composites offers unique opportunities to develop multifunctional materials with enhanced mechanical, electrical, and thermal properties [8]. Conductive carbon materials (e.g., graphite), transition metal oxides, and polymeric separators can contribute to improved reinforcement, conductivity, and durability in composite systems. Furthermore, advancements in processing techniques such as melt blending, solution casting, and in situ polymerization enable efficient incorporation of these recycled materials into polymer matrices. The motivation for this approach is driven by multiple factors. Economically, the reuse of battery-derived materials can reduce raw material costs and enhance the value chain of composite manufacturing. Environmentally, it significantly lowers carbon emissions and mitigates the ecological burden associated with mining critical elements such as cobalt, nickel, and lithium. Additionally, this strategy addresses growing concerns related to resource security and waste management in the battery industry [9-11].

However, several technical challenges must be addressed to realize the full potential of this approach. Battery degradation mechanisms—including lithium loss, structural changes in electrode materials, and electrolyte decomposition—affect the quality and performance of recovered materials. Moreover, issues such as material heterogeneity, interfacial compatibility with polymer matrices, and processing scalability require systematic investigation. Advanced characterization and surface modification strategies are essential to optimize the performance of battery-derived reinforcements in composite applications [12-14]. Recent studies on sustainable fiber-reinforced and recycled polymer composites have demonstrated significant improvements in mechanical performance, thermal stability, and environmental sustainability, emphasizing the growing importance of circular material utilization strategies in advanced engineering applications [15-19].

This review aims to provide a comprehensive analysis of the recycling and reinforcement of retired EV battery materials in polymer composites, focusing on material recovery, processing methodologies, composite performance, and sustainability aspects. By bridging the fields of battery technology and polymer composite engineering, this work contributes to the development of innovative, sustainable materials and supports the transition toward a circular and resource-efficient economy.

## LITERATURE REVIEW

### Battery Degradation Mechanisms and State-of-Health Assessment

The effective utilization of retired lithium-ion batteries in polymer composite applications requires a thorough understanding of battery degradation mechanisms and their impact on material properties. Battery aging is governed by complex and interrelated processes, including solid electrolyte interphase (SEI) layer growth, lithium plating under high charging conditions, and structural degradation of cathode materials through transition metal dissolution. These processes not only reduce electrochemical performance but also alter the surface chemistry, morphology, and structural integrity of electrode materials, which are critical for their reuse as composite reinforcements [20-22].

Degradation behavior varies significantly across battery chemistries such as nickel–manganese–cobalt (NMC), lithium iron phosphate (LFP), and nickel–cobalt–aluminum (NCA). Among these, LFP systems exhibit greater structural stability and longer cycle life, making them more suitable for secondary applications in polymer composites, whereas NMC materials offer higher conductivity but may suffer from compositional instability. Such variations directly influence the selection of battery-derived materials for composite fabrication [23-25].

State-of-health (SOH) assessment plays a crucial role in evaluating the quality and usability of recovered materials. Advanced diagnostic techniques, including incremental capacity analysis (ICA) and differential voltage analysis (DVA), enable non-destructive evaluation of degradation states. Additionally, machine learning approaches, such as support vector regression and particle filtering, provide accurate prediction of remaining useful life based on first-life operational data [26-28].

Understanding the relationship between degradation patterns and residual material performance is essential for optimizing recycling strategies. Batteries with severe degradation may exhibit compromised structural properties, limiting their effectiveness as reinforcement materials. Therefore, systematic SOH evaluation and material characterization are necessary to ensure reliable integration of battery-derived components into polymer composite systems [29].

### Repurposing Technologies and Remanufacturing Processes

The transition of retired lithium-ion batteries from automotive applications to material reuse in polymer composites involves a series of remanufacturing steps, including disassembly, separation, grading, and material recovery [30-31]. End-of-life batteries can follow three primary pathways: direct reuse, repurposing for secondary applications, and material recycling [32]. Among these, material recovery for composite integration is gaining increasing attention due to its ability to utilize even degraded battery components.

A major challenge in remanufacturing is cell heterogeneity, where variations in capacity, impedance, and degradation state exist among cells from the same battery pack [33]. Such inconsistencies necessitate careful sorting and grading to ensure uniformity in recovered materials. Advanced disassembly techniques, including automated and robotic systems, have been developed to improve efficiency, reduce labor costs, and enhance safety during battery processing [34].

Battery management system (BMS) considerations, while critical for second-life energy applications [35], also influence material recovery by providing diagnostic insights into cell condition and degradation history. This information supports selective recycling and classification of materials suitable for composite reinforcement. Recovered components include graphite, transition metal oxides, metallic foils, and polymer separators, which require further purification and processing before integration into polymer matrices. Grading and preprocessing techniques ensure consistency in particle size, composition, and surface properties, which are essential for achieving reliable composite performance [36-38].

### Economic Analysis and Market Dynamics

The economic viability of recycling retired EV batteries into polymer composites depends on material recovery efficiency, processing costs, and market demand for sustainable materials [39-40]. While traditional second-life applications focus on energy storage, material-level valorization offers a broader and more flexible value chain, enabling the utilization of degraded battery components that may not be suitable for reuse in energy systems [41].

Techno-economic studies indicate that second-life batteries can provide 11–28% cost advantages over new systems; however, uncertainties in pricing, transportation, and reconditioning remain key challenges [42]. From a materials perspective, incorporating battery-derived components such as graphite, metal oxides, and metallic foils into polymer composites can significantly reduce raw material costs while adding functional value, particularly in conductive and structural applications [43-44]. Reconditioning and grading processes improve the usability of recovered materials, but they also introduce additional costs that must be balanced against performance gains. The economic feasibility of composite integration is further enhanced by the growing demand for sustainable and recycled materials in automotive, construction, and electronic industries.

Market projections indicate rapid growth in EV battery waste generation, with global volumes expected to increase substantially by 2030 [45]. This trend creates a strong supply base for recycled materials and supports the development of circular economy-driven composite manufacturing. The integration of battery-derived materials into polymer composites presents a cost-effective and scalable approach, provided that challenges related to material consistency and processing efficiency are addressed [46].

## MATERIALS AND METHODS

### Materials and Methods

This review was conducted using a systematic methodology to critically evaluate the incorporation of recycled EV battery materials into polymer composite systems. The study focused on identifying material recovery techniques, composite fabrication methods, and comparative performance characteristics of battery-derived polymer composites. A structured literature search was performed using Web of Science, Scopus, ScienceDirect, and Google Scholar databases covering publications from 2015 to 2025. Keywords such as “EV battery recycling,” “lithium-ion battery waste,” “polymer composite reinforcement,” “battery-derived fillers,” “graphite-polymer composites,” and “sustainable composite materials” were used.

The methodology involved four major stages: (i) collection and screening of relevant literature, (ii) classification of recovered battery materials, (iii) comparative analysis of composite fabrication techniques, and (iv) sustainability and performance evaluation. Recovered battery materials including graphite, transition metal oxides, metallic foils, and polymer separators were analyzed based on their suitability as reinforcing agents or functional fillers in polymer matrices. Composite processing methods such as melt blending, compression molding, solution casting, extrusion, and in situ polymerization were comparatively evaluated based on dispersion efficiency, interfacial compatibility, thermal stability, and mechanical performance. In addition, the performance of recycled-material-based polymer composites was compared with conventional virgin-material composites using parameters such as tensile strength, thermal resistance, electrical conductivity, hardness, and durability. Environmental sustainability indicators including carbon emission reduction, waste minimization, resource conservation, and circular economy benefits were also critically analyzed.

## RECYCLING OF EV BATTERY MATERIALS

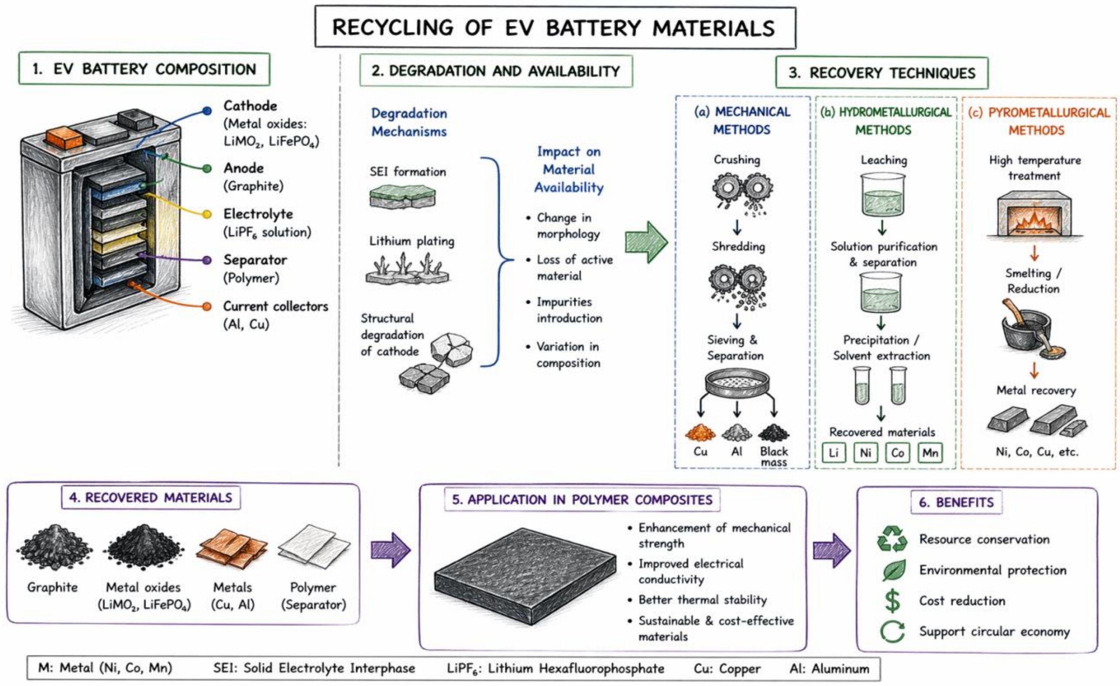


**Figure 1.** Recycling Strategies and Valorization of EV Battery Materials for Composite Reinforcement

### Comparison Between Recycled Battery-Based Composites and Conventional Polymer Composites

The recycling of electric vehicle (EV) batteries has emerged as a critical strategy for sustainable resource management, particularly due to the growing demand for lithium-ion batteries highlighted by the International Energy Agency [47]. These batteries contain valuable materials that can be effectively recovered and reused in polymer composite systems, thereby supporting circular economy principles and reducing dependence on virgin resources shown in (fig.1).

Lithium-ion batteries are composed of several key components, including graphite anodes, transition metal oxide cathodes (such as NMC and LFP), metallic current collectors (copper and aluminum), electrolytes, and polymeric separators [48]. Among these, graphite and carbon-based materials exhibit high electrical conductivity, making them suitable as functional fillers in polymer composites. Similarly, metal oxides can act as reinforcing agents, while polymer separators may be reused or blended within polymer matrices. The intrinsic properties of these materials provide opportunities for developing composites with enhanced mechanical strength, conductivity, and thermal stability [49-50].

During battery operation, degradation processes such as solid electrolyte interphase (SEI) formation, lithium plating, and structural breakdown of electrode materials alter their physicochemical properties. These changes influence the availability and quality of recovered materials, affecting their performance when incorporated into composite systems. For instance, degraded cathode materials may show reduced structural integrity, whereas graphite may retain significant conductive properties, making selective recovery and characterization essential [51-52].

Various recovery techniques have been developed to extract usable materials from spent batteries. Mechanical methods involve crushing, shredding, and physical separation, enabling the initial segregation of battery components [53]. Hydrometallurgical processes utilize aqueous solutions and chemical treatments to selectively recover metals and active materials with high purity [54-55]. In contrast, pyrometallurgical methods employ high-temperature processing to recover metallic fractions, although they may lead to the loss of certain components and higher energy consumption. Each method offers distinct advantages and limitations in terms of efficiency, cost, and environmental impact.

## CHALLENGES AND FUTURE PERSPECTIVES

The integration of retired EV battery materials into polymer composites presents significant opportunities; however, several challenges must be addressed to enable large-scale and reliable applications. One of the primary limitations is material heterogeneity, as battery components recovered from different cells and chemistries exhibit variations in composition, particle size, morphology, and degradation state. Such inconsistencies can adversely affect dispersion, interfacial bonding, and overall composite performance, necessitating effective sorting, grading, and surface modification strategies [56-58].

Another critical challenge lies in scale-up and industrial processing. While laboratory-scale studies have demonstrated promising results, translating these processes to industrial production requires cost-effective, energy-efficient, and reproducible methods for material recovery, purification, and composite fabrication. Issues related to contamination, handling safety, and process optimization must be systematically addressed to ensure commercial viability. Standardization is also a major concern, as the absence of uniform guidelines for the classification, processing, and utilization of battery-derived materials limits their widespread adoption. Establishing standardized protocols for material characterization, quality control, and performance evaluation is essential for ensuring consistency and reliability in composite applications [59-63].

Despite these challenges, future research offers substantial scope for advancement. Emerging approaches such as surface functionalization, hybrid composite development, and nanostructured reinforcement design can significantly enhance material compatibility and performance. Additionally, the application of artificial intelligence and machine learning for material selection, property prediction, and process optimization is expected to accelerate innovation in this field. Further studies focusing on long-term durability, environmental impact, and life cycle assessment will be crucial in validating the sustainability of these materials [64-68].

## CONCLUSION

The rapid expansion of electric vehicle adoption has intensified the need for sustainable management of end-of-life lithium-ion batteries. This review demonstrates that recycling and reutilization of EV battery materials in polymer composites offers a promising and efficient alternative to conventional disposal and energy-based second-life applications. Valuable components such as graphite, transition metal oxides, and metallic foils can be effectively recovered and incorporated as functional reinforcements, leading to improved mechanical strength, electrical conductivity, and thermal stability of composite systems.

The integration of battery-derived materials not only reduces dependence on virgin raw materials but also contributes significantly to environmental sustainability by lowering carbon emissions and minimizing waste. Advances in recovery techniques and composite processing methods have further enhanced the feasibility of this approach. The environmental benefits associated with recycling retired EV battery materials into polymer composites are substantial. This approach reduces landfill disposal of hazardous battery waste, minimizes extraction of virgin raw materials such as cobalt, nickel, and lithium, and decreases greenhouse gas emissions associated with mining and material processing. Furthermore, incorporation of recycled battery constituents into value-added composite products supports circular economy principles by extending material lifecycle and improving resource utilization efficiency. Consequently, this strategy contributes significantly toward sustainable engineering, waste reduction, and environmentally responsible materials development.

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