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Environmental and Health Impact Assessment of Electric Vehicle Battery Emissions: A Comprehensive Review and Mitigation Strategies

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Environmental and Health Impact Assessment of Electric Vehicle Battery Emissions: A Comprehensive Review and Mitigation Strategies

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Abstract. Electric vehicles (EVs) are increasingly recognized as a key solution to reduce greenhouse gas emissions and urban air pollution; however, their batteries present significant environmental and health challenges. This paper provides a comprehensive review of the life cycle assessment (LCA) of EV batteries, addressing impacts from production, use, and end-of-life stages. Results from existing studies indicate that while battery electric vehicles (BEVs) reduce fossil fuel dependence and overall GHG emissions, battery production contributes substantially to energy consumption, resource depletion, and toxic emissions. End-of-life management remains critical, as improper disposal increases environmental risks, whereas reuse and recycling can mitigate these burdens. The review highlights effective mitigation strategies, including sustainable material sourcing, cleaner manufacturing processes, design for durability, second-life applications, efficient recycling technologies, and supportive policy frameworks. By integrating these approaches, the environmental and health impacts of EV batteries can be significantly reduced, supporting global decarbonization and sustainable transportation goals.

INTRODUCTION

In recent years, electric vehicles (EVs) have emerged as a cornerstone of global strategies aimed at combating climate change and promoting sustainable development. EVs serve as a viable alternative to internal combustion engine vehicles (ICEVs)[1], offering substantial reductions in urban air pollution and greenhouse gas emissions from the transportation sector[2]. The number of electric vehicles in Uzbekistan is steadily increasing, contributing to a reduction in toxic and greenhouse gas emissions. However, it is essential to develop a comprehensive strategy to mitigate the environmental impact of harmful substances released from electric vehicles and their batteries. EVs are regarded as a key solution for mitigating urban air pollution and reducing greenhouse gas emissions within the transportation sector.

Studies in [3] have shown that passenger battery electric vehicles (PBEVs) can significantly reduce fossil fuel use and GHG emissions, especially with cleaner electricity sources. Projections indicate strong decarbonization potential by 2050, supporting global climate goals, though more region-specific models are needed. Plug-in electric vehicles (PEVs) can significantly reduce GHG emissions, especially with cleaner electricity. Studies show that early adoption is crucial, as delays lead to higher emissions that future clean battery production cannot offset. Most assessments still overlook changing energy mixes and upstream emissions[4]. The study in [5]evaluates the life cycle emissions of BEVs and gasoline cars in China. BEVs reduce greenhouse gas emissions by 35% and significantly lower volatile organic compounds (VOCs) and nitrogen oxides NO_X, but have slightly higher particulate matter ($PM_{2.5}$) and sulfur dioxide (SO_2) emissions. Smaller vehicles generally have lower emissions, with Class A vehicles showing the greatest potential for reduction. The study highlights the need for policies supporting clean energy, emission controls, and targeted vehicle class strategies to maximize BEV benefits. Results in another research [6] show advancing scientific modeling of socio-technical systems is essential for identifying rapid, cost-effective pathways to decarbonize transportation and address broader planetary and societal challenges. By integrating learning dynamics, feedback mechanisms, and diverse stakeholder behavior, such models can inform policies that accelerate innovation while minimizing systemic resistance, ultimately revealing the true potential of batteries and BEVs in combating climate change.

EXPERIMENTAL RESEARCH

The Life Cycle Assessment of Electric Vehicle Batteries

The Life Cycle Assessment (LCA) of EV batteries reveals that while EVs offer significant environmental benefits during their use phase—especially when powered by renewable energy—the overall sustainability of their batteries is heavily influenced by the upstream and downstream stages. Battery production, particularly the extraction and processing of raw materials like lithium, cobalt, and nickel, contributes substantially to energy consumption, greenhouse gas emissions, and ecological degradation. To minimize these impacts, it is essential to improve mining practices, optimize battery manufacturing processes through cleaner energy sources, and develop robust recycling and second-life strategies. Advancements in battery technology, circular economy approaches, and policy support for ethical sourcing and recycling infrastructure are critical to enhancing the environmental performance of EV batteries across their full life cycle.

The life cycle of batteries is typically divided into three main stages: production, use, and end-of-life (including the reuse of retired EV batteries and battery recycling), as illustrated in **Figure 1**. Battery production imposes a substantial environmental impact, primarily due to energy-intensive processes such as cathode material processing and electrode drying, with regional variations influenced by energy sources and industrial practices. In the use phase, increasing the share of renewable energy in electricity generation enhances the environmental benefits of batteries, while their performance also varies according to size. At the end-of-life stage, batteries can be repurposed for secondary applications and subjected to recycling processes to recover valuable materials.

In the reuse stage, batteries may undergo either remanufacturing or repurposing. Remanufacturing involves repairing or refurbishing EV battery packs for reuse in their original automotive applications, typically by original equipment manufacturers (OEMs). In contrast, repurposing entails reconfiguring batteries for lower-voltage applications such as grid-connected energy storage, backup power, auxiliary services, or power tools.

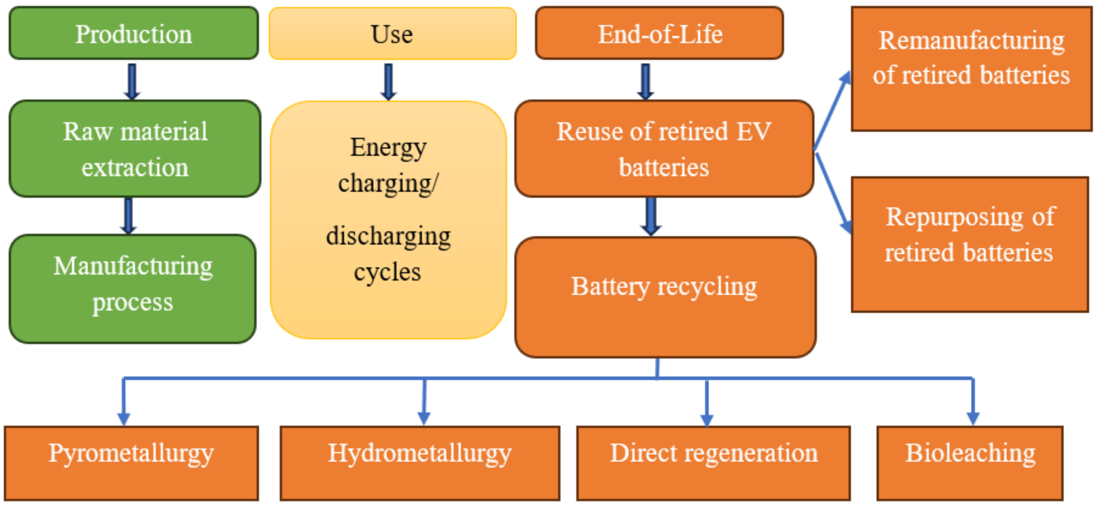

Figure 1. Life Cycle Assessment Framework of EV Batteries

Battery recycling can be carried out through four main methods: pyrometallurgy, hydrometallurgy, direct regeneration, and bioleaching.

Pyrometallurgy involves high-temperature pyrolysis to remove non-metallic components, followed by melting valuable metals into smelting materials or molten salts.

Hydrometallurgy includes pre-treatment, leaching, and metal recovery through chemical solutions.

Direct regeneration restores the crystal structure and electrochemical properties of electrode materials without the need for leaching.

Bioleaching (bio-hydrometallurgy) employs microorganisms such as bacteria, fungi, and archaea to extract metals from ores or battery waste.

Retired EV batteries retain 70–80% of their capacity, making direct disposal wasteful and environmentally harmful. Repurposing them for energy storage is more sustainable, and subsequent recycling or remanufacturing reduces raw material demand, supporting closed-loop battery production [7].

RESEARCH RESULTS

Table 1 Mitigation Strategies for Reducing Environmental Impacts of EV Batteries

Strategy	Description
Sustainable Material Sourcing	One of the most effective ways to reduce environmental impacts is through the sustainable extraction and sourcing of raw materials. This includes the adoption of responsible mining practices, adherence to ethical labor standards, and the use of alternative or lower-impact materials (e.g., reducing cobalt content through material substitution or next-generation chemistries).
Cleaner Manufacturing Processes	Battery manufacturing is highly energy-intensive. Transitioning to renewable energy sources for battery production, improving process efficiency, and adopting low-emission manufacturing technologies can significantly lower greenhouse gas emissions and reduce cumulative energy demand.
Design for Durability and Reuse	Enhancing battery design to improve lifespan and performance can reduce the need for frequent replacements and associated resource use. Modular designs also facilitate easier disassembly and reuse, enabling extended life through second-life applications.
Second-Life Applications	Repurposing used EV batteries for stationary energy storage—such as backup power or grid support—can extend their functional lifespan and offset the environmental impacts of battery production. However, standardized assessment frameworks are needed to accurately evaluate the benefits of these second-life uses.
Efficient Recycling and Material Recovery	Developing and implementing advanced recycling technologies (e.g., hydrometallurgical and direct recycling methods) can recover valuable materials like lithium, nickel, and cobalt, thereby reducing the demand for virgin resource extraction and minimizing waste.
Policy and Regulatory Support	Governments and regulatory bodies play a crucial role in encouraging sustainable battery practices. Policies promoting recycling infrastructure, producer responsibility, and eco-labeling can incentivize manufacturers and consumers to prioritize environmentally responsible options.
Lifecycle-Based Decision Making	Incorporating life cycle thinking into product design, policy development, and procurement processes ensures that environmental considerations are accounted for at every stage of the battery's life, from raw material extraction to end-of- life management.

In the LCA of an automotive battery, it is recommended to consider the following environmental impact categories: global warming potential, acidification, eutrophication, ozone layer depletion, particulate matter formation, abiotic resource depletion, human toxicity, ecotoxicity, and Cumulative Energy Demand (CED)[8]. These categories provide a comprehensive evaluation of the battery's environmental footprint throughout its entire life cycle.

Most environmental impact studies of EVs tend to overlook the effects related to the disposal, reuse, or recycling of vehicle components. These end-of-life stages are often excluded, despite their significant role in the overall sustainability and environmental footprint of EVs[9]. It is often qualitatively asserted that the environmental impacts of EV batteries could be reduced by allocating a portion of those impacts to their post-vehicular applications, such as use in stationary energy storage systems. Battery manufacturing and end-of-life processes remain areas of active research and development. Notably, battery production represents a significant portion of the overall manufacturing emissions associated with electric vehicles[10]. However, a more comprehensive understanding of the value and energy storage potential of second-life batteries is required before such impact allocations to downstream use can be accurately and justifiably made.

MITIGATION STRATEGIES TO REDUCE HARMFUL EFFECTS

To address the environmental burdens associated with EV batteries, several mitigation strategies can be implemented throughout the battery's life cycle. These strategies aim to reduce negative impacts across key categories such as global warming, resource depletion, toxicity, and energy consumption. As illustrated in **Error! Reference source not found.** several methods are available to reduce harmful effects throughout the battery life cycle. Through the strategies given above, we can reduce the harmful substances that pose a threat to the environment and human life when using electric vehicle batteries.

CONCLUSIONS

The conducted review demonstrates that electric vehicle batteries, while enabling significant reductions in greenhouse gas emissions, introduce notable environmental and health challenges across their life cycle. The production stage is the most energy- and emission-intensive due to material extraction and processing, whereas inadequate end-of-life management amplifies ecological risks. Implementation of life cycle–based mitigation strategies, including sustainable raw material sourcing, low-emission manufacturing, design optimization for durability, and advanced recycling technologies, can substantially reduce cumulative environmental impacts. Integration of second-life applications and circular economy principles further enhances system efficiency. Overall, adopting a comprehensive, life cycle–oriented approach is essential for improving the environmental performance of EV batteries and ensuring the sustainability of future transport systems.

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