

Process Optimization in EV Battery Manufacturing: Reducing Waste and Improving Efficiency

ABSTRACT

Aim: To examine the process optimization in EV battery manufacturing to improve efficiency via waste reduction.

Problem Statement: Traditional vehicles with internal combustion engines have been observed as the main influencers of greenhouse gas emissions. Electric vehicle (EV) batteries are becoming speedily attractive as one of the most important products of this era. It is highly imperative to find lasting solutions to these emissions reductions as the climate crisis becomes more prominent and persistent.

Significance of Study: EVs are observed to be sustainable options because of zero emission of greenhouse gases during operation. A major factor that substantiates the significance and functionality of EVs in the absence of internal combustion engines is the battery.

Methodology: Recent relevant published articles in the area of process optimization in EV battery manufacturing via waste reduction were consulted. The review process involved a comprehensive literature search conducted in reputable academic databases such as Web of Science, Scopus, IEEE Xplore, and ScienceDirect.

Discussion: In this review article, different management techniques that are aimed at alleviating the negative environmental impacts were presented. The critical role that effective management plays in attaining carbon neutrality was recognized. These emphasized the need for an economical recycling infrastructure capable of transporting and collecting batteries from diverse sources. Proper policies and strategies are essential for sorting and collecting waste batteries. It is necessary to identify that during the production phase, internal combustion engine vehicles may outperform EVs despite the environmental advantages of EVs over internal combustion engine vehicles. Furthermore, the improper handling of EV waste could cause significant social and environmental risks. Thus, numerous benefits are attached to applying comprehensive management strategies to address these concerns. Various emerging methods for recycling and reusing EV batteries were evaluated. Among these methods, direct recycling exhibited encouraging environmental performance.

Conclusion: In conclusion, waste reduction is a vital procedure for process optimization in EV battery manufacturing to improve its efficiency.

Keywords: EV Battery Manufacturing, Waste Minimization, Efficiency Improvement, Process Optimization, Zero Emission

1. INTRODUCTION

Electric vehicle (EV) batteries are speedily attractive as one of the most important products of this era [1]. It is highly essential to find lasting solutions to greenhouse gas emissions reduction as the climate crisis becomes more prominent and persistent. Traditional vehicles having internal combustion engines are the main influencers of these emissions. On the contrary, EVs are observed to be sustainable options because of zero emission of greenhouse gases during operation. A major factor that substantiates the relevance and functionality of EVs in the absence of internal combustion engines is the battery. The most common and significant choice for EVs is the lithium-ion battery as a result of its extremely high energy density, lightweight nature, and compact size. Thus, the optimization of lithium-ion battery technology is vital to enhance the performance of EVs and efficiency to pave the way for a sustainable future [2].

As shown in Figure 1, the demand for EVs is envisaged to move higher in some decades to come as its demand is at a high value at the moment. The worldwide electric vehicle market is anticipated to develop considerably over the next years [3]. The number of electric vehicles expected to be on the road by 2030 is 145 million based on the data from the International Energy Agency (IEA). This was predicted under the current policy scenarios with the possibility to reach about 230 million in an accelerated case. This growth is influenced by the policies put in place by the government which decline the costs of batteries and increase the consumer's demand purposely for cleaner transportation alternatives. Many factors influence this trend while financial incentives are the main driving force [4]. Initially, EVs were exorbitantly costly, but as technology has improved and manufacturing processes have become more effective, costs have gradually reduced. Furthermore, the undependability and increasing gasoline costs make EVs a progressively attractive alternative, despite their greater upfront cost. Moreover, societal styles are moving towards better environmental consciousness [5].

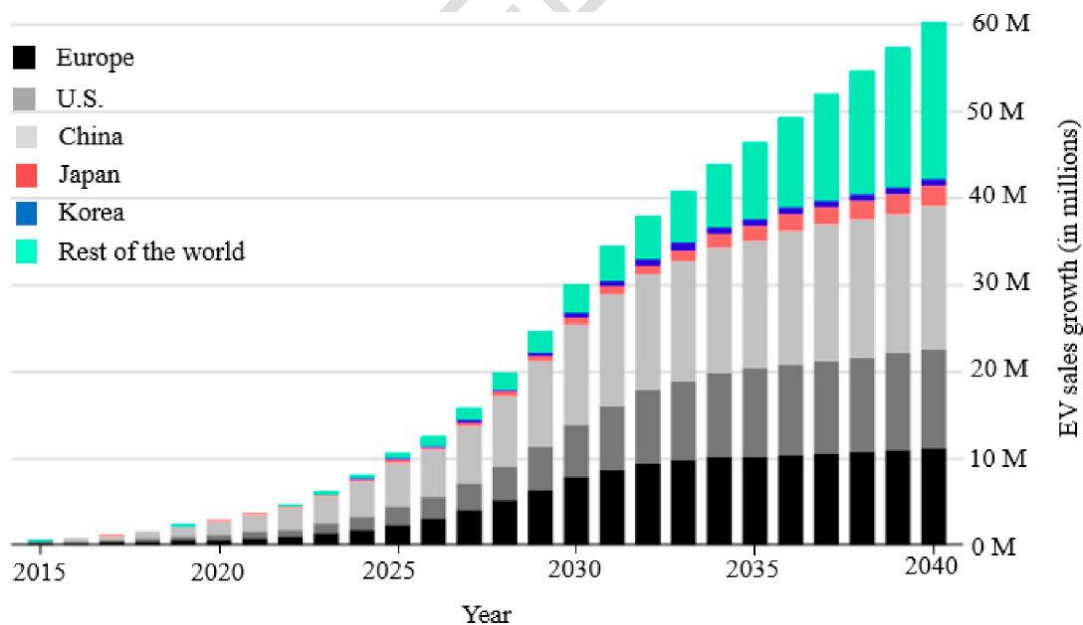


Figure 1: Global demand for EV

A large number of people are becoming more conscious of their contributions to climate alteration and feel good about driving vehicles with a reduced carbon footprint. Many countries are targeting how to eliminate or minimize the production of traditional vehicles while inspiring

the adoption and manufacturing of EVs. France, the UK, Netherlands, Germany, and many other countries are dedicated to the objectives of the Paris Agreement and are working towards strategies to reduce the production of internal combustion engine vehicles by 2040 [6]. Supportive measures are also being introduced by Governments such as electricity subsidies and purchase incentives to inspire consumers to pick electric vehicles (EVs) in countries like Japan, Finland, Germany, Austria, and France. These factors jointly suggest that the request for EVs will continue to develop, strengthening the positive outlook for the EV market.

One of the most speedily rising subsectors of the renewable energy industry is the electric vehicles (EVs) market. Worldwide sales of EVs have continued to rise over the years. As shown in Figure 2, EV sales reached 10 million units in 2022. This progress in EV sales is projected to continue, with more than 2.3 million units sold in the first quarter of 2023. Projections show that by the end of year 2024, more than 14 million units will have been sold demonstrating a significant 35% rise from 2022 sales. This flow in EV sales reveals the increasing acceptance of sustainable mobility, indicating an encouraging change in the automotive sector toward decreasing greenhouse gas emissions [7]. However, the improved usage of EVs shows a substantial encounter in handling end-of-life batteries. Management of used EV batteries is still in the initial stages of improvement and needs optimum approaches for reprocessing and recycling. Recycling and reprocessing stand as the best long-term alternatives for ensuring the economic, social, and environmental sustainability of this market. Recycling can generate profits via the alleviation of the toxicity of end-of-life products and assist nations decrease imports [8].

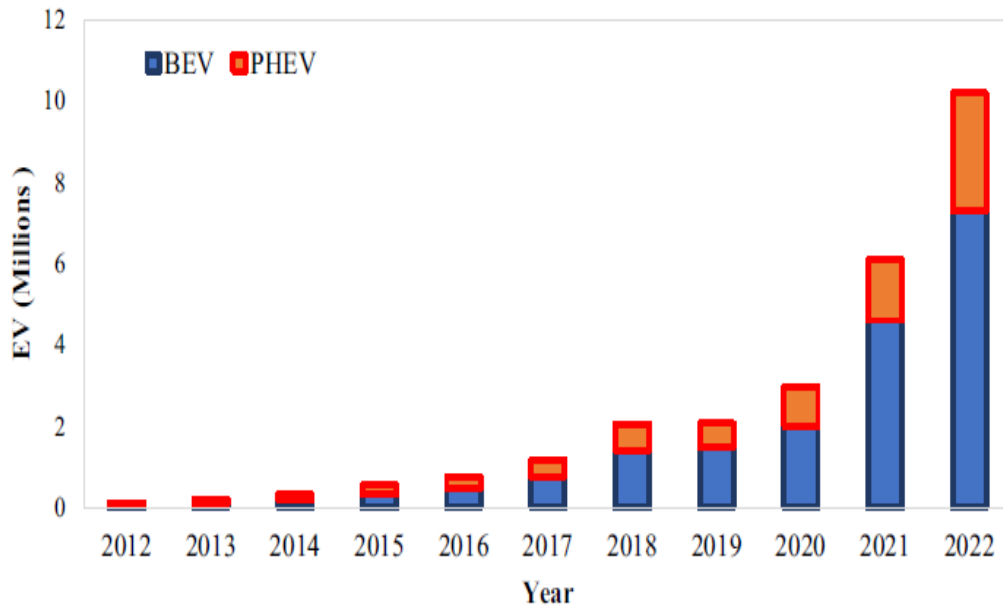


Figure 2: Global electric car stock between 2012 and 2022 for Plug-in hybrid electric vehicles (PHEVs) and Battery electric cars (BEVs)

Lithium-ion batteries (LiBs) have considerably influenced the EV industry. They store energy via a reversible decrease of lithium ions and typically comprise metal oxide cathodes and graphite anodes as shown in Figure 3. LiBs possess benefits such as long lifespan, high energy density, and quick charging when compared with conventional batteries. Their

efficiency and durability made them popular consumer choices. LiBs find extensive applications in different sectors, including electronics, transportation, and other industrial applications. The increasing LiBs demand has caused a reduction in their cost. Although EVs have a reduced general climate and environmental impact, their disposal poses environmental worries. Therefore, substantial research is essential to decrease the toxicity of EV batteries and to expand the disposal framework [9].

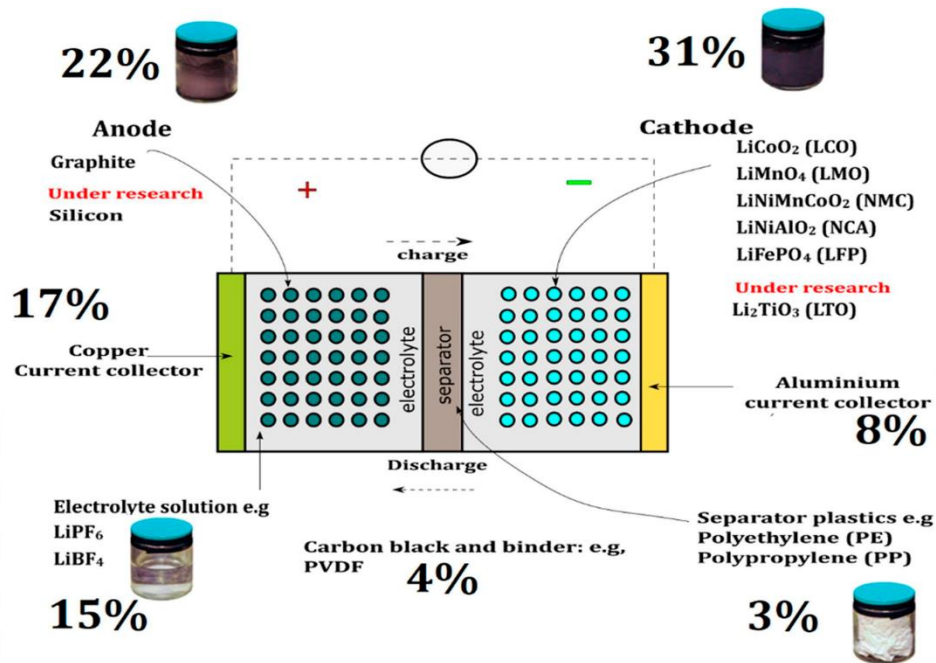


Figure 4. Schematic diagram showing the various components of a lithium-ion battery

Removal and safe handling of LiBs from EVs is a noteworthy trial that needs to be addressed. LiBs are categorized as hazardous waste as a result of the risks of explosion, fire, and toxic chemical release when mishandled or damaged. Hence, the collection of waste LiBs from the market is a complicated problem and comprises challenges including the efficient and safe removal of LiBs from BEVs and their effective transportation to recycling facilities. LiBs removal from EVs poses significant safety risks resulting from the batteries' potential for thermal runaway and high energy content causing explosions or fires if handled wrongly [10]. The complication of EV designs additionally complicates the removal process needing specialized training, knowledge, and tools to securely remove LiBs from EVs at end-of-life. The deficiency of standardization in battery-pack designs can constrain the removal process efficiency as it may need various techniques and tools for different EV models. This can increase the cost and time linked with the removal process. Currently, robotic disassembly systems have been established but face problems centered on non-standardized battery-pack designs [11].

The lifespan of EV batteries is between 8 and 10 years until they lose about 20–30% of their initial capacity. These decommissioned batteries signify a potential foundation of valuable materials and energy. However, they also present a substantial environmental affliction. The appropriate and safe management of large-scale decommissioned EV batteries has materialized as an increasing environmental worry. Many EV batteries worldwide end up

discarded despite the prospective for recycling or reusing EV batteries, though not categorized as hazardous in some nations, still pose disposal threats [4-6]. Landfilling these batteries without appropriate treatment can cause groundwater and soil contamination as a result of heavy metals leaching such as cobalt, lithium, copper, and nickel. Additionally, many other toxic additives such as volatile organic electrolytes and ionic compounds may also leach into the groundwater and soil causing broad environmental contamination. Furthermore, the reaction between the electrolytes and water may form several toxic gases that harmfully affect human health. Also, retired batteries may possess a high voltage which poses an electric shock risk. Finally, the disposed batteries can emit toxic fumes, cause explosions, and contaminate water bodies. This review paper critically examines the process optimization in EV battery manufacturing via waste reduction and management to improve its efficiency.

2.0 PROCESS OPTIMIZATION IN EV BATTERY MANUFACTURING VIA REUSING OF RETIRED BATTERIES

Retired EV batteries still comprise about 70–80% of their initial capacity representing an opportunity to improve their lifespan via applying them in numerous other applications. Additionally, reusing EV batteries will offer sufficient time to enhance capacity improvement and recycling technologies. Two methods are usually adopted in extending the batteries' life: remanufacturing and repurposing. Remanufacturing means prolonging the expected life span of an EV battery via refurbishment or repair; however, this method needs the retired battery to be in good condition. Even though the remanufacturing of EV batteries possesses encouraging potential in minimizing the environmental impact, there is not a substantial remanufacturing application now. In another way, retired batteries can be applied and repurposed in an extensive range of applications [12]. For instance, the application of retired EV batteries in energy storage systems can increase the environmental purposes of EVs. For residential usage, the use of retired EV batteries compared to the application of new batteries lowered the carbon emissions and electricity costs by 7–31% and 12–57% respectively. Similarly, a study compared the use of fresh batteries with retired EV batteries for residential purposes. It was noticed that it reduced global warming potential and abiotic depletion potential mineral resources by 44–49% and 93% respectively. The application of retired vehicle batteries in other areas not only avoids new battery manufacturing but also causes significant environmental purposes that enhance Ev's environmental performance.

2.1 RECYCLING OF RETIRED BATTERIES AS PROCESS OPTIMIZATION IN EV BATTERY MANUFACTURING

Recycling is known to be among the most universally applicable alternatives for retired EV batteries as a result of its ease of management and great scalability. This approach provides many economic and environmental advantages via the reduction of the demand for virgin materials. Present recycling approaches mainly focus on recovering valuable metal elements such as cobalt, nickel, and lithium. These methods include pyrometallurgy, hydrometallurgy, and direct recycling [13]. Numerous studies have evaluated the environmental advantages of recycling methods of EV batteries. Direct recycling exhibits the most favorable environmental performance among these methods with 34–81% GHG reduction when compared with hydrometallurgy and pyrometallurgy. However, this methodology is still in its initial stages and is only being verified on a laboratory scale. To effectively enhance and handle the environmental performance of the enormous wave of EV-battery waste, it is necessary to attain closed-loop battery production via advancing recycling techniques and intensifying the scale of applications [14].

Direct recycling encompasses recovering components from wasted EV batteries via direct physical recycling. The process removes the need for difficult chemical processes. The treatment choice involved in direct recycling is based on electrochemical or physicochemical treatment to revive the damaged sections and electrochemical properties so they can be applied as a starting material or as new materials for new battery development. Direct recycling includes two approaches which are lithiation and replenishment [15]. Relithiation supplements lithium ions back to the exhausted batteries while replenishment entails hydrometallurgy to dissolve the recycled cathode material back into the leaching solution. Development in the direct recycling technique includes the advancement of minor working conditions in hydrothermal lithiation. For instance, direct hydrothermal lithiation of cathode material at 100 °C has been achieved via a low-cost redox mediator. The recovered cathode formed maintained its structural, morphologic, and electrochemical characteristics [10]. Figure 5 shows the general schematic diagram of pretreatment processes in LiBs recycling. The step comprises discharging, dismantling, mechanical treatment, sieving, separation, dissolution, and thermal treatment.

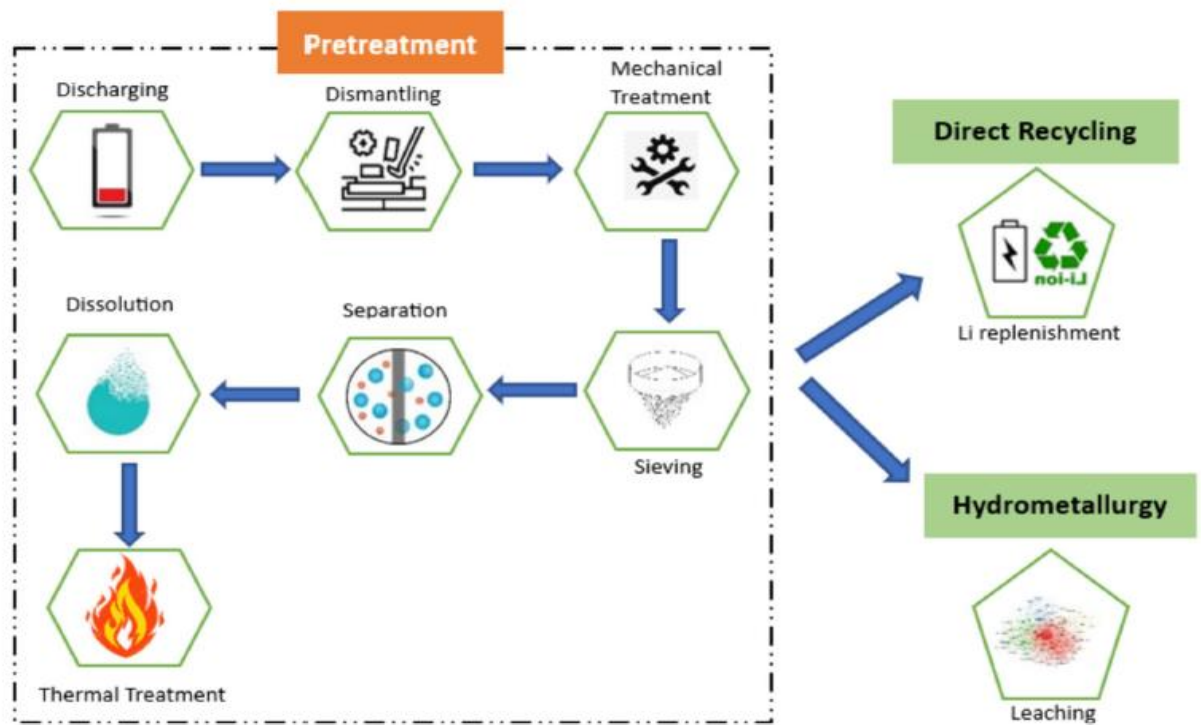


Fig. 6 General schematic diagram of pretreatment processes in LiBs recycling

Direct recycling is still in its promising stages and with shortcomings. One of the problems is the need to distinguish cathode types in advance to adopt the proper rejuvenation technology. In addition, cathode chemistry is quickly progressing, which may make the recycling of cathodes outdated [16]. To increase direct cathode regeneration methods, EV batteries with better efficacy and reduced cost are important. First, the research community should emphasize the effect of various cathode chemistries on the direct recycling process and optimize the process. Furthermore, combining other recycling techniques with direct recycling to develop a closed-loop manufacturing approach for lithium-ion batteries can expedite the

battery recycling process. In addition, more studies should pay attention to the likely difficulties of direct recycling techniques to assess the financial and environmental benefits of direct recycling techniques over existing ones [17].

3.0 EV WASTE-BATTERY MANAGEMENT VIA EMERGING GREEN TECHNOLOGIES

New green technologies are evolving with circular economy and carbon neutrality goals. These complement conventional recycling skills and have advanced EV battery management. Some of the adopted techniques involve using green leaching treatment for battery recycling, bioleaching, and waste for waste methods.

3.0.1 GREEN LEACHING TREATMENT FOR BATTERY RECYCLING

Leaching is the process of changing material from a solid substance to a solvent (leaching or agent lixiviant). This bleaching agent is applied to selectively extract the preferred materials from their respective ores. Numerous substances such as inorganic acids, microbes, emerging green solvents, and organic acids have been used as lixivants in extracting various wasted batteries. Green solvents could make a key approach for the recovery and recycling of cherished materials from waste batteries and contribute to a more circular economy [18].

3.0.2 BIOLEACHING

Bioleaching is novel in the recycling of spent LiB. The procedure involves biosorption and bioleaching. Bioleaching utilizes acids which are decomposed via microorganisms to solubilize metals while biosorption utilizes fungi, yeast, or algae to form coordinate, complex, or proceed via ion exchange mechanisms with the intended metal. Microorganisms adopt inorganic or carbon-based materials as their energy origins. Varied kinds of microorganisms including heterotrophic bacteria, fungi, and chemolithotrophic prokaryotes are applied for spent EV batteries bioleaching. Although bioleaching is eco-friendly, inexpensive, promising for reducing carbon emission, and requires less energy input, however, the process is restricted by long duration, slow kinetics, and complexities involved in microorganism incubation. Other factors that affect bioleaching efficiency include metal toxicity, pulp density, redox potential, air supply, microbial growth rate, and temperature [19].

Bioleaching offers a promising technique for recycling LiBs, providing an eco-friendly option to traditional pyrometallurgical methods. However, ensuring that only the targeted metals, such as cobalt, lithium, and nickel are leached from the battery materials while leaving non-target metals behind remains a noteworthy challenge. In addition, the utilization and identification of microbial strains active in bioleaching LiB components, along with the optimization conditions (pH, temperature, pH), is a multifaceted task. Moreover, attaining efficient and consistent leaching on a large scale poses a major hurdle. Therefore, these challenges should be addressed in future studies to enhance the viability and efficiency of this method [20].

3.0.3 WASTE FOR WASTE

The waste-for-waste technique provides the potential to utilize disposable materials as an environmentally friendly and sustainable approach to recycling waste batteries. The use of food waste materials as an evolving recycling method for recycling LIBs has been presented. Notably, the utilization of fruit peels and vegetable oils as electrolytes in battery manufacturing is a possible research direction [21]. Furthermore, agricultural waste including grape seeds, tea wastes, orange peels, and food wastes containing reducing agents offer viable substitutes to the use of harsh H_2O_2 in metal dissolution from wasted EV batteries. Recently, tea waste was employed as a reducing agent to attain over 98% Co, Li, Ni, and Mn from wasted LIB cathode. In another study, waste derived from waste peel including lemon, pomelo, papaya, honeydew, orange, and mango was applied as lixiviant to attain over 90% Li and Co extraction from wasted-battery cathode material. This approach provides an improvement toward a circular economy and sustainable purposes.

3.1 CASE STUDY OF EV WASTE BATTERIES MANAGEMENT

Over the last three decades based on the performance of EV batteries, LIBs have become more efficient in terms of storage capacity, sustainability, and cost productivity. As LIBs have a restricted working period, it is essential to properly manage them over the end-of-life to stop environmental damage and recuperate valuable metals. With these increasing worries, numerous countries have stepped up to improve recycling skills or safe disposal approaches. Safe battery collection for recycling or disposal is the main task in waste management. Several countries have developed appropriate collection points for end-of-life EV-battery waste. However, the waste EV batteries collection rate is much lower than what is required. For example, only one-third of LIBs were collected in China in 2019, which indirectly stresses the urgency for recycling. The recycling and collection rates for e-waste according to the Global E-waste Monitor Report in 2020 are around 10% in America, 43% in Europe, and 12% in Asia followed by the lowest recycling rate in Africa [22].

3.2 CHALLENGES AND PROSPECTS OF WASTED-BATTERY MANAGEMENT

The adoption of a cradle-to-cradle technique that focuses on carbon neutrality is vital to attain sustainable waste-battery management. This starts from well-designed collection practices which ensure that environmental protection is incorporated into the pretreatment step. The recycling arrangement should avoid emitting toxic gases or causing secondary pollution. Green technologies can also a vital role in both EV recycling and manufacturing. For example, electricity generation from renewable sources like wind or solar power can considerably decrease the carbon footprint of EVs [23].

Additionally, the incorporation of recycled materials in production can eradicate the necessity for virgin resources. Intermittent current supply can provide substantial benefits in electrometallurgical recycling of EV batteries. Energy efficiency is boosted by intermittent current via the reduction of power usage during non-active periods leading to economic savings. Merging various energy sources including renewables minimizes reliance on fossil fuels promoting sustainability. Intermittent supply can also influence grid stability via balancing of power usage during low and high-demand periods causing a stable energy system. Furthermore, cost savings can be achieved via scheduling of recycling operations when there are off-peak hours in which the electricity rates are reduced. The Incorporation of Industry 4.0

ideologies in EV-battery recycling entails battery-type screening and efficient process management. The robotic system must be intelligent and adaptable enough to separate and distinguish batteries of different formats and types. In addition, it must be economical to make recycling a more attractive technique [17].

Hybrid systems of green technologies provide substantial leeway in the growth of efficient EV waste-battery recycling practices and provide better environmental sustainability with considerably lower global warming potential. The combination of technologies like supercritical CO₂ with two or more encouraging compounds can result in a sustainable and suitable battery recycling solution. While bioleaching processes have mainly been dedicated to cathode recycling, commercialization efforts must accept other battery components like electrolytes and anodes. The recovery of anode graphite from spent LiBs can be attained via straightforward minimal operational techniques and the application of inexpensive microbial nutrition, growing the lucrateness of the LiBs bioleaching method. Moreover, other EV battery components such as electrolytes should be utilized and examined for other applications [24].

4. CONCLUSION

This review article has comprehensively examined the public health and environmental consequences linked with the recycling and disposal of end-of-life EV batteries. Different management techniques which are aimed at alleviating the negative environmental impacts were presented. The critical role that effective management plays in attaining carbon neutrality was recognized. These emphasized the need for an economical recycling infrastructure capable of transporting and collecting batteries from diverse sources. Proper policies and strategies are essential for sorting and collecting waste batteries. It is necessary to identify that during the production phase, internal combustion engine vehicles may outperform EVs despite the environmental advantages of EVs over internal combustion engine vehicles. Furthermore, the improper handling of EV waste could cause significant social and environmental risks. Thus, numerous benefits are attached to applying comprehensive management strategies to address these concerns. Various emerging methods for recycling and reusing EV batteries were evaluated. Among these methods, direct recycling exhibited encouraging environmental performance. In conclusion, waste reduction is a vital procedure for process optimization in EV battery manufacturing to improve its efficiency.

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