

Sustainable EV Battery Management: Process Optimization, Recycling, and Green Technologies for Retired Batteries

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. Lithium-ion batteries elimination from electric vehicles possesses substantial safety dangers resulting from the batteries' potential for thermal runaway and high energy content causing explosions or fires if handled wrongly.

Significance of Study: Electric vehicles are observed to be sustainable options because of zero emission of greenhouse gases during operation. The removal and safe handling of LiBs from EVs is a noteworthy trial that requires attention.

Methodology: Recent relevant published articles in the area of process optimization in EV battery manufacturing via waste reduction were consulted. A broad literature search from reliable academic databases such as Scopus, Web of Science, ScienceDirect and IEEE Xplore.

Discussion: This review paper examines various kinds of management procedures which are targeted at alleviating the adverse environmental impacts. The active role of effective management in attaining carbon neutrality was identified. There is need for an economical recycling infrastructure having the capacity of transporting and collecting batteries from different locations. It is necessary to identify that during the production stage, vehicles having internal combustion engines may perform excellently than EVs despite the environmental advantages of EVs over internal combustion engine vehicles. Furthermore, the inadequate handling of EV waste can cause substantial social and environmental dangers. Thus, numerous benefits are attached to applying broad management approaches to address these worries. Various evolving techniques for recycling and reusing EV batteries were examined. Out of these methods, direct recycling exhibited encouraging environmental ability. The manuscript discusses how process optimization in EV battery manufacturing can be attained through reusing of retired batteries together with recycling of retired batteries as process optimization in EV battery manufacturing. Green leaching treatment for battery recycling, bioleaching and waste for waste were identified as the EV waste-battery management techniques via emerging green technologies.

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 among the most important commodities 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. 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. In order to lower the environmental influence and carbon footprint emanating from utilizing internal combustion engine vehicles, it is essential that industries and governments should contribute significantly in promoting the use of electric vehicles globally [2]. Studies have shown huge contributions of government and agencies in this regard in few decades ago. Lower air pollutants and CO₂ emissions have been per attributed to the use of EVs as a result of higher electric motors efficiency when compared with the traditional internal combustion engines. This resulted from the electricity generation sources as a replacement for vehicle tailpipes [3]. Also, emissions of CO₂ can be extremely minimal by charging the battery via renewable energy source. Traction battery has been identified as a major EVs component but as time progresses; its storage ability diminishes calling for instant replacement basically after eight to ten years [4].

The efficiency and durability of lithium-ion batteries have placed them higher amidst the popular consumer options. LiBs find extensive usage in different areas such as electronics, transportation, and other industrial purposes [5]. The increasing LiBs demand has caused a reduction in their cost. Although EVs have drastically reduced the overall climate and environmental influences, their discharge causes environmental worries. Therefore, substantial investigation is essential to decrease the toxicity of EV batteries and to expand the discharge framework [2]. Figure 1 is the schematic diagram showing the various components of a lithium-ion battery. The cathode takes the larger percentage of 31% while the separator plastic takes the smallest percentage of 3%. The percentage of anode, electrolyte solution, copper current collector and aluminium current collector were respectively 22%, 15%, 17% and 8% [6].

Removal and safe handling of LiBs from EVs is a noteworthy trial that requires attention. LiBs are categorized as harmful waste as a result of the threats of fire, explosion and deadly chemical discharge when mishandled. Hence waste LiBs gathering from the market is a complicated issue and comprises problems including the efficient and safe elimination of LiBs and their effective conveyance to recycling amenities. LiBs elimination from EVs possesses substantial safety dangers resulting from the batteries' potential for thermal runaway and high energy content causing explosions or fires if handled wrongly. Numerous EV batteries were lastly disposed despite the prospective for recycling or reusing EV batteries, though not classified as lethal in some countries, still pose discharge threats. The complication of electric vehicle designs additionally hardens the elimination process needing distinct training, knowledge, and instrument to securely eliminate LiBs from EVs at the last phase [7]. The deficiency of regularization in designing battery-pack can limit the elimination process efficiency due to various techniques requirements and tools for various EV models. This can bring rise in cost and time linked with the elimination process. Currently, robotic disengagement systems have been established but battling with challenges centered on non-regularized battery-pack arrangements [8].

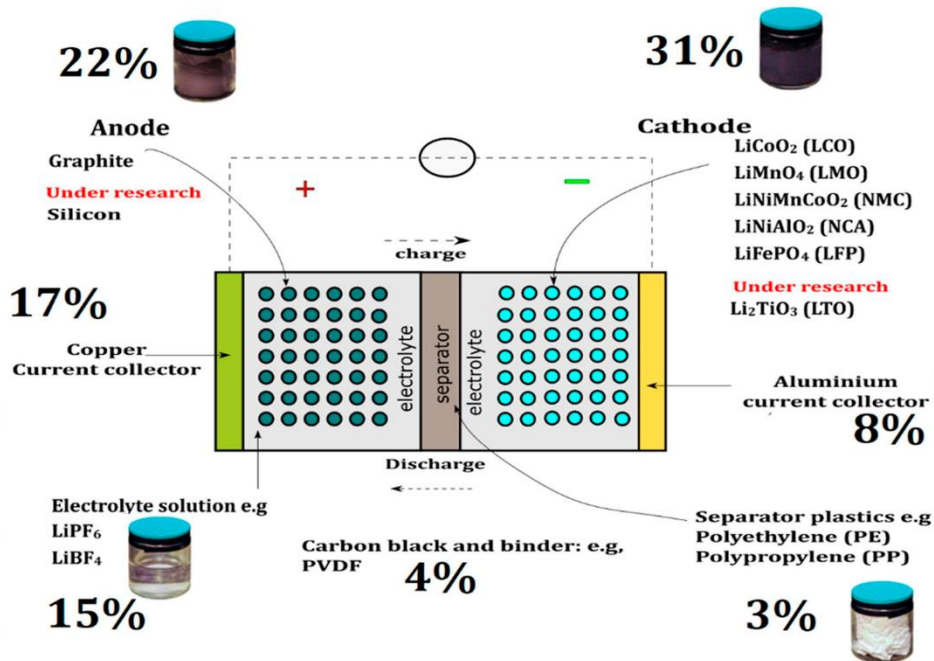


Figure 1: Percentages of different lithium-ion battery components

The rapid advancement in electric vehicles applications and systems of energy storage has been so contributory in improving worldwide awareness of environmental protection and sustainable energy. This has also been a catalyst to enhancing the use of lithium-ion battery and global adoption of battery technology. With these, it has been predicted that a huge volume of retired electric vehicles would be in circulation in years to come as a result of the short lifespan of lithium-ion batteries [9]. A battery's capacity life in electric vehicle application majorly stops when about 80% of its maximum storage efficiency remains as a result of the substantial driving range reduction with degradation of the battery. The lifetime of electric vehicle batteries could vary between four to fourteen years and this is being influenced by rapid discharge and high temperature; and some other environmental and weather factors. It is imperative to critically look for battery replacement in the lifecycle of electric vehicles because the conventional vehicles usually last ranging from ten to sixteen years. With this, there is high expectation of retired batteries in the nearest future as a result of the present speedy improvements in the worldwide stock of electric vehicles [10].

It is expected that the storage capacity of batteries deteriorate over time as energy storage devices. This alters their performance and lowers the lifecycle. This also ultimately necessitates their retirement calling for proper disposal and handling. Two major problems can evolve from not handling retired batteries properly which include (1) disruption of the ecological system posing dangerous threat and (2) wastage of recoverable and valuable resources [11]. Thus, reuse and efficient means of reorganization are essential in handling the retired batteries because of their high significance to economic, social, and environmental development in ameliorating scarcity of resources and managing environmental pollution emanating from their disposal. Furthermore, the reaction between the electrolytes and water in retired battery cells can form numerous gases which are toxic in nature and can inflict injury to human health. Also, used batteries can possess a high voltage which has the potential of electric shock risk. Lastly, the discarded batteries may emit toxic fumes, pollute water bodies and lead to explosions [12].

Numerous problems and challenges still stand out which are needed to be tackled despite the attached benefits of battery reuse and recycling [13]. The biological, chemical and physical methods are part of the known emerging techniques which create room for technical assistance and new opinions for battery recycling purposely to reduce costs and increase the efficacy. The establishment of reuse markets for recovered retired batteries from EVs is highly important. A typical LIB used in EV still has the potential to retain 70–80% of its initial storage capacity despite its non-demanding market value for driving of EVs. The integration and incorporation of immobilized energy storage systems of different scales like commercial facility, residence and power grid can revive the reuse of huge number of retired EV batteries for a second time. These provide a better cheaper energy storage alternative having beneficial life of about ten years [14]. These can equally improve alternating renewables grid penetration. The reuse of retired EV batteries partly balances the necessity for energy storage batteries production [7].

This review paper critically examines the process optimization in EV battery manufacturing via waste reduction and management to improve its efficiency. In this paper, Section 2.0 of the manuscript discusses the historical trend and prospective usage of electric vehicles and retired lithium-ion battery generation. The technological contribution of some developed nations to reuse and recycling of retired lithium-ion battery was also discussed in this section. Section 3.0 handles the recycling of retired batteries as process optimization in EV battery manufacturing was critically examined. Also this section discusses the EV waste-battery management via emerging green technologies. Green leaching treatment for battery recycling, bioleaching and waste for waste. The conclusion was addressed in Section 4.0.

2.0 HISTORICAL TREND AND PROSPECTIVE USAGE OF ELECTRIC VEHICLES AND RETIRED LITHIUM-ION BATTERY GENERATION

In 2020, the electric vehicles deployment generated huge volume of lithium-ion battery as wastes in the United States of America in the range of 1 to 23 thousand tonnes. In China, the total volume of electric vehicle batteries generated as wastes was between 120–170 thousand tonnes in the same year. The presence of retired batteries poses high risk to the environment and may adversely alter the ecosystem and affect humans' health. Figure 2 presents the worldwide new registrations evolution of EVs battery between the year 2005 and 2015. A gradual increase across many developed nations was noticed between 2005 and 2012 while rapid increase was recorded between 2013 and 2015 as indicated in the diagram [15].

In another survey presented further beyond 2015 as shown in Figure 3, the global stock of electric car stock and its respective sale attained about 10 million units while reports indicated that approximately 2.3 million units were sold in the first-four months in 2023. Equally, it was projected that more than 14 million units would have been vended by the tail end of the present year 2024 [16]. Further, studies projected the rapid sale of electric vehicles to attain approximately 60 million in some advanced countries of the world (such as China, America, Japan, Korea, Europe and so on) by the year 2040 as shown in Figure 4. A rapid increase has been indicated in the Figure between 2024 and 2037 with possible sale of more than 40 million units. Generally, the diagram revealed a consistent rise in the EV sale.

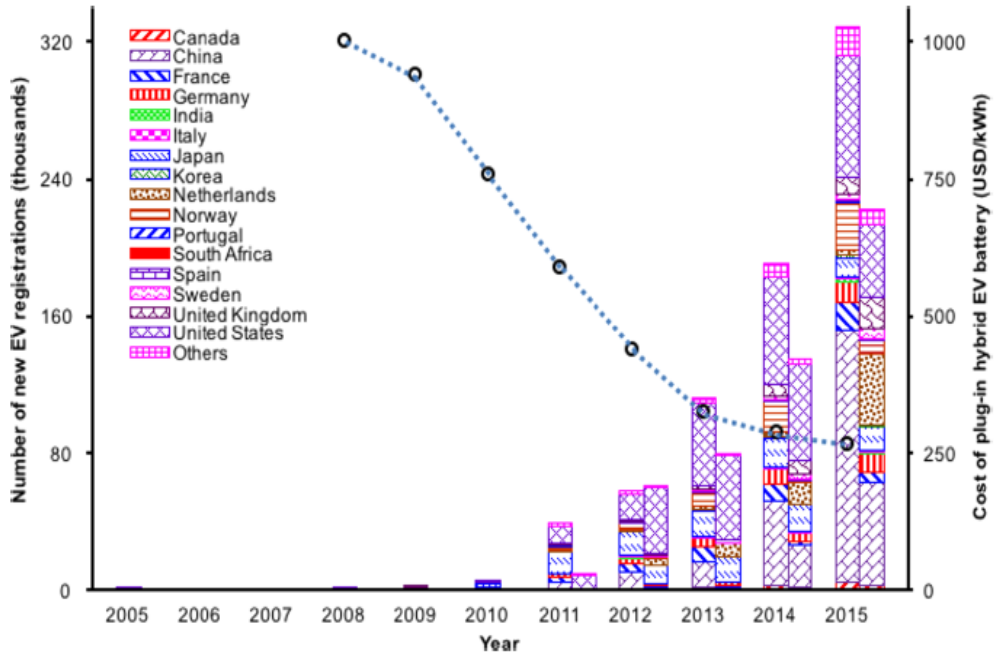


Figure 2:Worldwide new registrations evolution of EVs battery

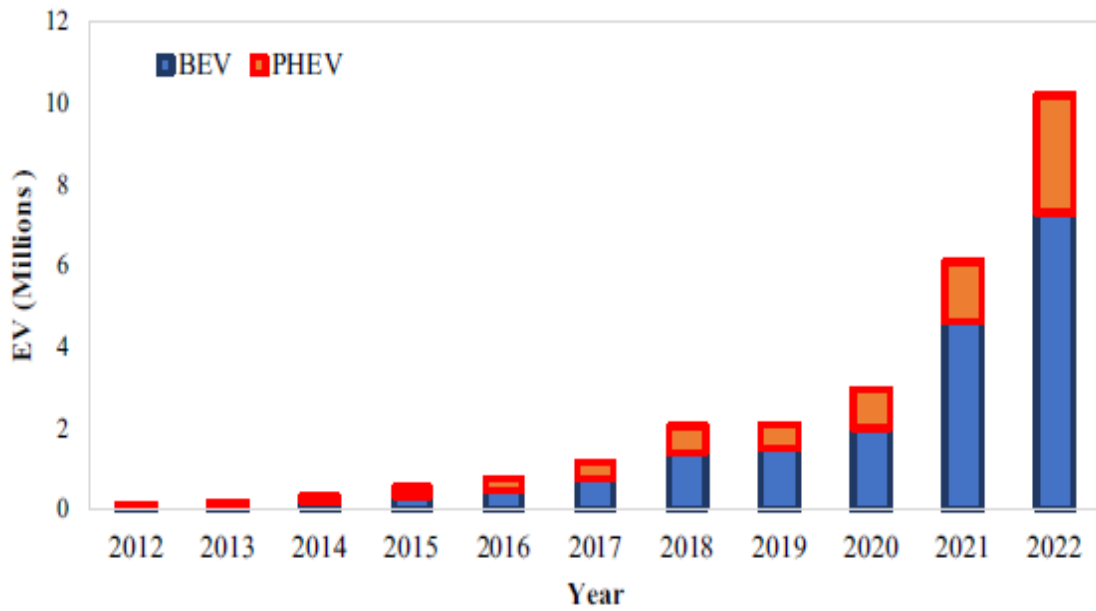


Figure 3: Pictorial representation of world electric car stock between 2012 and 2022

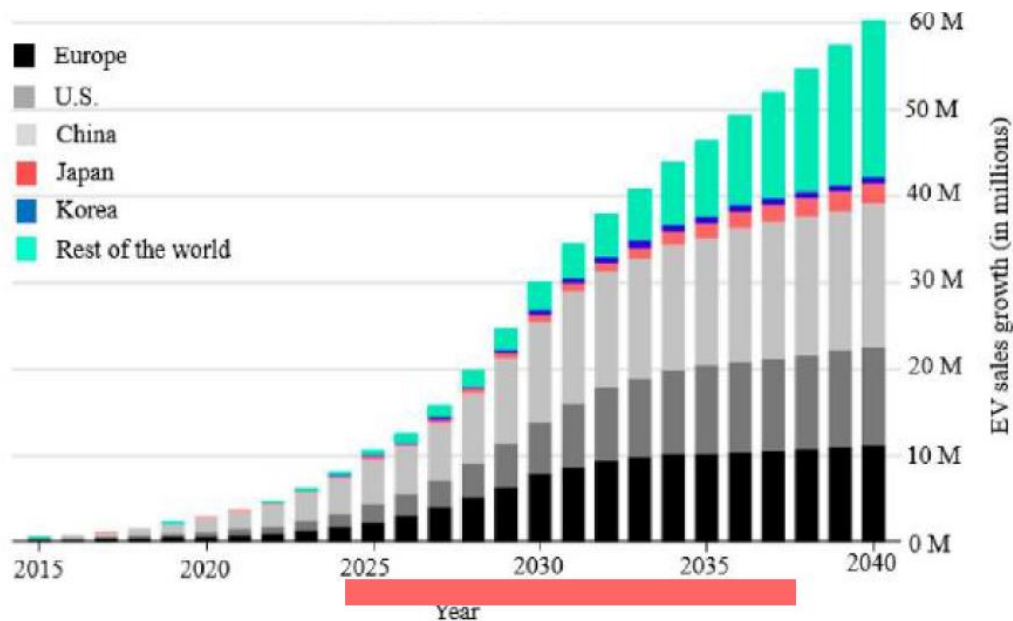


Figure 4: Projection of EV sale in advanced nations of the world till 2020.

2.1 TECHNOLOGICAL CONTRIBUTION OF SOME DEVELOPED NATIONS TO REUSE AND RECYCLING OF RETIRED LITHIUM-ION BATTERY

From the previous indications, vital roles have been executed by China being one of the leading marketers of electric vehicles. Numerous policies have been made and put in place together with some positive impact research regarding the management of retired Lithium-ion batteries. A major one is the adoption of the recycling technique. The need for reuse and recycling of Lithium-ion batteries have opened wide gaps in the research area calling for urgency [17]. Many advanced countries around the globe have invested and created internationally broad battery recycling procedures. For instance in Europe, laws have been enacted charging manufacturers of Lithium-ion batteries in proper disposal and recycling of retired batteries. Adopting this legislation would serve as a means of encouraging the utilization of advanced techniques to enhance the rates of material recovery [18]. In North America as well, facilities that are capable of recycling large volume of retired Lithium-ion batteries have been established alongside some incentives which on the other way round encourages the recycling of the retired batteries. A technological innovation using a hybrid pyro-metallurgical and wet recycling process for LIBs has been developed in Japan. This has contributed positively in the recovery rate of rare metals available in lithium-ion batteries. All these have shown the commitment of developed nations to battery recycling [19].

Currently, suggestions are being made on the technologies of recycling and reuse of Lithium-ion batteries can be improved and enhanced. The development of certification protocols was recommended together with quality standards for retired batteries in order to ascertain their effectiveness and safety. This will equally promote the reuse programs for the EV batteries [20]. Additionally, all hands must be on desk in the standardization of battery models and components is also essential by the manufacturers of batteries and EVs. This will enhance the compatibility of cross-manufacturer and also support the establishment of tracking and identification procedures for batteries. Via these, the EV economic viability can

be improved together with the facilitation of the development of major reuse opportunities for retired batteries [21].

Furthermore, the incorporation of artificial intelligence into the techniques via which retired Lithium-ion batteries can be reused and recycled has been suggested. This entails the adoption and utilization of big data in Lithium-ion batteries recycling in order to positively influence the efficacy and efficiency of the reuse and recycling processes via the optimization of intelligent transportation and establishment of an information-sharing devices and means [22]. Adopting this will give room for handling of retired lithium-ion battery on large scale with the use of cascaded energy storage systems to enhance the technology of dynamic reconfigurable battery network which further enhances the safety and consistency of the configured systems. This has been tested on a large scale and yielded positively. This proffers solutions to many of the single unit handling the processing of the batteries reuse and recycling. However, there are still some limitations and research gaps that are needed to be bridged. There is still need to conduct research on state of health variation with time and usage. Also, some influencing factors such as shapes, battery capacity, charge/discharge power and various battery brands should be considered [19].

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

One of the most promising ways via which retired EV batteries can be adequately managed and optimized is recycling. This resulted from its huge scalability attribute and friendliness in terms of management. Numerous environmental and economic benefits have been accorded with this approach. Numerous experiments have evaluated the environmental advantages of EV batteries recycling technique. Direct recycling exhibits the most favorable environmental performance among these methods with 34–81% GHG decrease on comparison with hydrometallurgy and pyrometallurgy [23]. Thus, this methodology is still in its initial phases and is verified on a laboratory measure. In direct recycling, direct physical recycling approach is used in components recovery from retired EV batteries which eliminates the necessity for highly tasking and costly chemical processes. The procedure involves using electrochemical or physicochemical treatment methods to resuscitate the retired or affected parts of the battery and revive their electrochemical properties in order for them to be used as fresh materials for the new battery production. Direct recycling includes two approaches which are lithiation and replenishment [15]. The lithium ions are supplemented back to the used batteries via relithiation while the recycled cathode material is dissolved back into the leaching solution using hydrometallurgy. Development in the direct recycling method involves the incorporation of slight working conditions in hydrothermal lithiation.

Figure 5 is the schematic representation of pretreatment procedures in LiBs recycling. The step comprises discharging, dismantling, mechanical treatment, sieving, separation, dissolution, and thermal treatment. Direct recycling at its promising phases still possesses some shortcomings. Among the problems is the need to distinguish cathode types in order to adopt the proper rejuvenation technique. Additionally, cathode chemistry is quickly progressing, which can turn cathodes recycling to be outdated [16]. To increase direct cathode renewal methods, EV batteries having excellent performance and reduced cost are important. Emphasis should be laid on the effect of various cathode chemistries on the process optimization and direct recycling by research community. Furthermore, the combination of other recycling techniques with direct recycling technique in order to develop a closed-loop production approach for lithium-ion batteries can expedite the battery recycling

process [24]. Additionally, future studies should pay attention to the likely difficulties of direct recycling techniques in order to evaluate the financial and environmental benefits of direct recycling techniques over already existing ones [17].

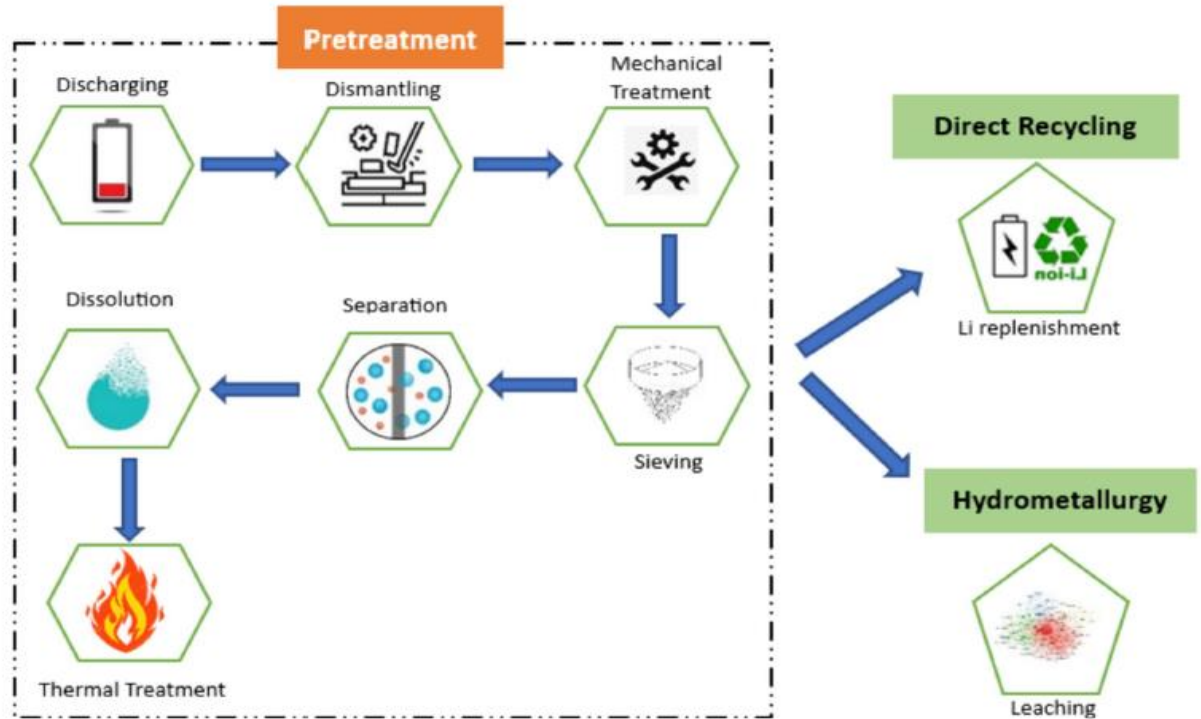


Figure 5: Pretreatment procedures in LiBs recycling

3.1 EV WASTEBATTERY MANAGEMENT VIA EMERGING GREEN TECHNOLOGIES

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

3.1.1 GREEN LEACHING TREATMENT FOR BATTERY RECYCLING

Leaching involves material transformation into a solvent from a solid substance. The leaching reagent is applied to optionally extract the preferred materials from their ores respectively. Numerous substances like inorganic acids, microbes, evolving green solvents and organic acids have been used as lixivants in extracting various discarded batteries. Green solvents can make a substantial approach in the recovery and recycling of cherished products from discarded batteries and positively influence a circular economy [18].

3.1.2 BIOLEACHING

Bioleaching is novel in the recycling of used LiB. The procedure entails biosorption and bioleaching. Bioleaching utilizes acids which are decomposed via microorganisms in order to solubilize metals while biosorption utilizes fungi, algae and yeast in order to form coordinate, complex, or proceed via ion exchange procedures with the intended metal. Microorganisms adopt inorganic or carbon-based substances as their energy origins. Varied types of microorganisms such as 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 procedure is restricted by long duration, complexities and slow kinetics involved in the incubation of microorganism. Other parameters that affect bioleaching efficacy include metal toxicity, pulp density, redox potential, air supply, microbial growth rate, and temperature [19]. Bioleaching offers an encouraging technique for LiBs recycling, providing a sustainable option to conventional pyrometallurgical methods.

3.1.3 WASTE FOR WASTE

The waste-for-waste technique utilizes disposable substances as an environmentally friendly and sustainable method to recycling discarded batteries. Studies have revealed the potentials of using remnants from food waste as an innovative recycling approach for LIBs. Journals have presented how vegetable oils and discarded peels from different fruits were being used as electrolytes during battery production [24]. The discarded fruit peels exhibited excellent reducing agent attributes as substitutes to the conventional H_2O_2 applied in the dissolution of metal present in wasted EV batteries. In recent time, study has utilized tea waste as a reducing agent to recover more than ninety-eight percent of cobalt, lithium, nickel and manganese from the cathode of discarded. Other studies used wasted peels from mango, papaya, pomelo and so on as lixiviant to recover more than ninety percent of lithium and cobalt from the cathode of wasted-battery using extraction process [25-28]. This is an astonishing and promising technique of managing wastes to solve waste problems from discarded EV batteries [29].

3.2 CASE STUDY OF EV WASTE BATTERIES MANAGEMENT

In the past three decades based on the efficiency of EV batteries, LiBs have become more effective with reference to storage ability, sustainability, and cost implication. Because of the limited working period of LIBs, it is essential to properly handle them over the last phase to stop environmental havoc and recuperate treasured metals. With these increasing worries, numerous nations are working towards improving recycling skills or safe discarding approaches [30]. Safe battery gathering for recycling or disposal is the key waste management task. Numerous nations have developed appropriate collection locations for exhausted EV-battery waste. However, the waste EV batteries collection rate is lower than required. For example in 2019, one-third of the LiBs were gathered in China, which incidentally stresses the quest for recycling [31]. The recycling and collection rates for e-waste based on the Global E-waste Monitor Report in 2020 are around 10% in America, 43% in Europe, and 12% in Asia with Africa having the lowest recycling rate [22].

4. CONCLUSION

Different management techniques targeting at alleviating the adverse environmental influences were presented. The vital role that efficient management acts in attaining carbon neutrality was recognized. These emphasized the need for an economical recycling infrastructure having the capacity of transporting and collecting batteries from different

locations. It is necessary to identify that during the production stage, vehicles having internal combustion engines may perform excellently than EVs despite the environmental advantages of EVs over internal combustion engine vehicles. Furthermore, the inadequate handling of EV waste can cause substantial social and environmental dangers. Thus, numerous benefits are attached to applying broad management approaches to address these worries. Various evolving techniques for recycling and reusing EV batteries were examined. Out of these methods, direct recycling exhibited encouraging environmental ability. The manuscript discusses how process optimization in EV battery manufacturing can be attained through reusing of retired batteries together with recycling of retired batteries as process optimization in EV battery manufacturing. Green leaching treatment for battery recycling, bioleaching and waste for waste were identified as the EV waste-battery management techniques via emerging green technologies. In conclusion, waste reduction is a vital procedure for process optimization in EV battery manufacturing to improve its efficiency.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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