JIMESE
Journal of Innovation Materials, Energy, and Sustainable Engineering
JIMESE 3(1): 21–39
ISSN 3025-0307

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Innovation in regeneration of graphene and nmc electrodes from lithium-ion battery waste through an environmentally friendly method

Jesaya Hansel[1,*]
[1] *Department of Chemistry, Faculty of Science and Mathematics, Diponegoro University, Semarang, Central Java, 50275, Indonesia.*
*Correspondence: Jesayahansel97@gmail.com

Received Date: June 30, 2025 Revised Date: July 30, 2025 Accepted Date: July 31, 2025

ABSTRACT
Background: The problem of lithium-ion battery (LIB) waste that has not been optimally addressed poses serious risks to the environment and strengthens dependence on primary metal mining. The limited availability of efficient and environmentally friendly recycling methods encourages the need for innovative approaches in the recovery of active materials from used electrodes. This study aims to evaluate the potential of a combination of two alkali-acid regeneration methods for graphene- based anodes and low-temperature molten salt for Nickel Manganese Cobalt (NMC) cathodes as a sustainable strategy in LIB waste treatment. **Methods:** The study was conducted through a critical literature review of various national and international scientific publications, focusing on the purification effectiveness, morphological characteristics, crystal structure, and electrochemical performance of the regenerated materials. **Findings:** The analysis results show that the alkali-acid method is effective in selectively removing impurities and is able to increase the specific capacity of the anode to 359 mAh/g, approaching the theoretical capacity of commercial graphene . Meanwhile, the NMC cathode regenerated through the molten salt method and combined with graphene through a simple solid-state mixing showed a capacity of 158.1 mAh/g at a current of 0.5C with good cycle stability. The integration of these two methods synergistically improves electron conductivity, cycle efficiency, and electrode structural stability. In addition to its technical advantages, this approach also utilizes relatively safe and readily available chemicals, making it relevant for both laboratory and industrial applications. The proposed process is competitive with commercial materials and has the potential to be implemented in the economical and industrial-scale remanufacturing of 18650 batteries. **Conclusion:** These findings significantly contribute to strengthening the battery recycling ecosystem in Indonesia and support the achievement of sustainable energy targets. Furthermore, reducing the volume of hazardous and toxic waste (B3) and optimizing the reuse of high-value materials support the implementation of circular economy principles that align with national policies in the energy and environmental sectors. **Novely/Originality of this article:** The novelty of this research lies in the integration of two selective and environmentally friendly regeneration methods in one processing system, which has not been widely developed in previous literature, thus offering a new applicable framework for LIB waste processing towards sustainable industrialization.

KEYWORDS: alkali-acid and low-temperature molten salt methods; lithium-ion battery recycling; regeneration of graphene and nmc.

1. Introduction

Indonesia, as a country endowed with abundant natural resources, faces considerable challenges in meeting its growing energy demands. This is driven by a projected population

Cite This Article:
Hansel, J. (2025). Innovation in regeneration of graphene and nmc electrodes from lithium-ion battery waste through an environmentally friendly method. *Journal of Innovation Materials, Energy, and Sustainable Engineering, 3*(1), 21-39. https://doi.org/10.61511/jimese.v3i1.2025.2157

exceeding 280 million by 2025 (Desviandini & Karyana, 2022) and an average economic growth rate of approximately 5% per year over the past decade (World Bank, 2021). The nation's continued heavy reliance on fossil fuels-which accounted for around 84% of the primary energy mix in 2021 (ESDM, 2023)-not only poses serious environmental consequences but also increases vulnerability to fluctuations in global energy prices. Addressing these challenges requires a strategic transition toward renewable energy, with battery technology playing a central role in energy storage systems and the development of battery electric vehicles (BEVs), which are essential components of a modern, low-emission energy infrastructure.

To support this transition, the Government of Indonesia has implemented a series of regulatory frameworks. The National Energy General Plan/*Rencana Umum Energi Nasional* (RUEN), enacted through Presidential Regulation No. 22 of 2017, sets a target of achieving a 23% share of new and renewable energy (NRE) in the national energy mix by 2025, along with accelerating the adoption of electric vehicles (Febriananingsih, 2019). In addition, Ministry of Energy and Mineral Resources Regulation No. 50 of 2017 governs the utilization of NRE for electricity supply, outlining provisions related to tariff structures, developer selection, and fiscal incentives (Nugroho & Kurniawan, 2021). The government also aims to ensure that electric vehicles constitute 23% of the national vehicle fleet by 2030, as part of its broader strategy to enhance energy security and reduce dependence on fossil fuels. Collectively, these policy measures reflect Indonesia's firm commitment to reducing greenhouse gas emissions and achieving its Nationally Determined Contribution (NDC) targets under the Paris Agreement.

However, the renewable energy transition faces significant challenges in the management of Lithium-Ion Battery (LIB) waste, which poses environmental and social risks due to the extraction and disposal of critical materials such as lithium, cobalt, and nickel (Jin et al., 2022). If left unaddressed, improper disposal of LIB waste may lead to groundwater contamination, toxic air emissions, and health hazards in surrounding communities. In this context, the application of circular economy principles-reduce, reuse, and recycle (3R)-is essential for minimizing reliance on primary resource extraction while maximizing the recovery of high-value materials from spent batteries (Wei et al., 2023). Although recycling technologies such as hydrometallurgy and pyrometallurgy have been extensively developed, they still encounter limitations, including high energy requirements, the generation of secondary waste, and elevated operational costs (Li et al., 2024). These constraints have prompted the search for alternative solutions that are both environmentally and economically viable.

One promising direction is the adoption of greener recovery techniques, particularly molten salt-based methods for cathode regeneration and alkali–acid treatments for anode restoration. These approaches offer lower carbon footprints by reducing the use of hazardous chemicals and minimizing secondary emissions. In particular, low-temperature molten salt processing enables the selective recovery of transition metals from degraded NMC cathodes, while alkali–acid regeneration restores the structural and electrochemical integrity of graphene-based anodes. Both methods utilize relatively benign reagents such as sodium hydroxide (NaOH) and hydrochloric acid (HCl), effectively removing impurities without generating harmful by-products (El Mounafia et al., 2023). Additionally, molten salt systems facilitate the recovery of valuable metals like nickel and cobalt, offering a more sustainable alternative to conventional thermal or chemical routes (Zhou et al., 2024). When combined in a solid-state regeneration framework, these techniques yield composite electrode materials with improved structural order, conductivity, and electrochemical performance, thereby enhancing both resource efficiency and long-term sustainability in battery production (Kosenko et al., 2024).

Scaling up battery material recovery technologies to the industrial level presents Indonesia with a strategic opportunity to establish itself as a global hub for battery manufacturing and recycling, capitalizing on its abundant nickel reserves. With approximately 21 million tons of nickel-more than 50% of global reserves (U.S. Geological Survey, 2023)-Indonesia is uniquely positioned to lead in the downstream processing of critical battery materials. The adoption of environmentally friendly technologies, such as the alkali–acid process for anode regeneration and the low-temperature molten salt method for cathode recovery, has the potential to significantly enhance production efficiency while minimizing environmental degradation. These processes avoid the use of highly hazardous chemicals and reduce the generation of secondary waste, enabling the efficient recovery of key metals such as lithium (Li), nickel (Ni), and cobalt (Co) (Fan et al., 2019; Lan et al., 2024).

Industries that incorporate these innovations can produce high-performance battery components with reduced material loss and lower environmental footprints, while also contributing to job creation and long-term sustainable economic growth. This aligns with Indonesia's broader clean energy transition strategy and industrial value-added goals. For instance, Indonesia Battery Corporation (IBC) has announced plans to establish a domestic battery recycling facility by 2031 as part of the national nickel downstreaming roadmap and efforts to advance clean energy infrastructure (IBC, 2023). To accelerate this transition, robust government support in the form of fiscal and non-fiscal incentives remains essential. Policy instruments such as the raw nickel export ban implemented in 2020 have already succeeded in attracting foreign direct investment and encouraging the localization of battery supply chains (Mubarok & Kartini, 2024). Complementing these efforts, comprehensive marketing strategies-including international partnerships and the development of domestic technological capabilities-are crucial for enhancing Indonesia's global competitiveness. By strengthening its role in the international battery ecosystem, Indonesia can not only promote sustainable industrial development but also contribute meaningfully to the global response to climate and environmental challenges.

2. Methods

This study adopts a non-experimental approach in the form of a structured literature review aimed at identifying, analyzing, and synthesizing a wide range of information related to lithium-ion battery (LIB) waste treatment. The primary focus lies in exploring the development of regenerated graphene-based anodes and NMC cathodes as innovative technological solutions to address battery waste challenges. Additionally, this review is contextualized within Indonesia's broader energy transition agenda, particularly the shift from fossil fuels to renewable electricity-based systems. Through critical and comprehensive examination of current literature, this study is expected to support the advancement of environmentally responsible and sustainable battery recycling strategies.

The information utilized in this study was sourced from various credible and up-to-date scientific publications, including national and international journals, peer-reviewed research articles, and technical reports. The primary databases accessed were Elsevier, the Royal Society of Chemistry, MDPI, Wiley Online Library, and ResearchGate. Literature selection was guided by criteria such as publication date (preferably from the last 5–10 years), scientific rigor, and direct relevance to LIB waste processing, regeneration, and recycling innovation. These sources provide a robust evidence base to support the discussion of best practices and emerging methods in the field.

The data collection phase involved synthesizing information from selected sources by summarizing, comparing, and connecting key findings to illustrate the evolution of treatment methods. For instance, the regeneration of graphene anodes has progressed from the conventional Hummers method-which poses environmental hazards-toward the more eco-friendly and selective alkali–acid method. Similarly, the regeneration of NMC cathodes has shifted from conventional hydrometallurgical processes to low-temperature molten salt methods that are more energy-efficient and environmentally sustainable. This synthesis enables a comprehensive understanding of current trends and technological advancements, forming a foundation for proposing integrated recycling pathways.

At the data analysis stage, each reference was assessed for validity, credibility, and thematic alignment. Both qualitative and quantitative analysis techniques were applied to identify common patterns, research gaps, and key performance indicators across studies. The resulting comparative analysis of anode and cathode regeneration techniques was used to evaluate the feasibility of developing a unified composite electrode system with enhanced structural and electrochemical properties. The goal is to improve the performance of lithium-ion batteries while promoting sustainable waste management practices. The entire framework of this literature review is structured systematically to provide direction for future research and practical implementation in battery material recovery.

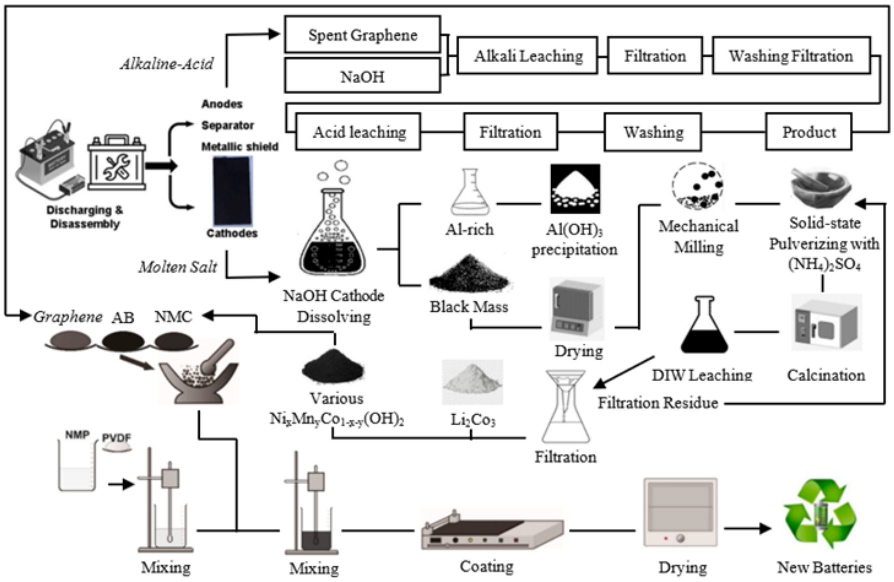


Fig. 1. Mechanism of processing regenerated graphene anode and NMC-G cathode into new lithium-ion batteries
(Ji et al., 2024; Qi et al., 2022; Vu et al., 2024; Wang et al., 2018; Wang et al., 2014; Zhang et al., 2023a; Zhao et al., 2022).

The evaluation of data and information sources is expected to provide a comprehensive overview of the research topic and ensure the consistency and validity of the collected information. Accordingly, this study aims to consolidate various findings into a solid conclusion and contribute to the development of innovative solutions for lithium-ion battery waste treatment.

3. Results and Discussion

3.1 Characterization and testing results of graphene anode

3.1.1 Morphological analysis

Scanning Electron Microscope (SEM) analysis was conducted to evaluate the morphological changes and surface structure of graphene before and after the regeneration process using the alkali-acid method. The SEM observations were performed at an accelerating voltage of 10 kV with magnifications ranging from 5,000× to 50,000× to enable detailed visualization of surface texture and microstructure. As shown in Figure 2(a), the untreated graphene exhibited a rough and irregular surface morphology, with numerous white particulate deposits identified as impurity compounds such as Al_2O_3, SiO_2, Fe_2O_3, and MnO_2. These inorganic residues are known to interfere with the structural stability and electrochemical properties of graphene, limiting its performance as an anode material in lithium-ion batteries. After undergoing alkali-acid treatment followed by thermal processing, Figure 2(b) reveals that the graphene surface became significantly smoother and more uniform, while the layered (lamellar) structure appeared more defined and orderly. This morphological improvement indicates successful removal of most impurities without compromising the carbon framework, and also suggests that the graphene's hexagonal crystalline structure remained intact, thereby preserving its electrical conductivity and mechanical robustness.

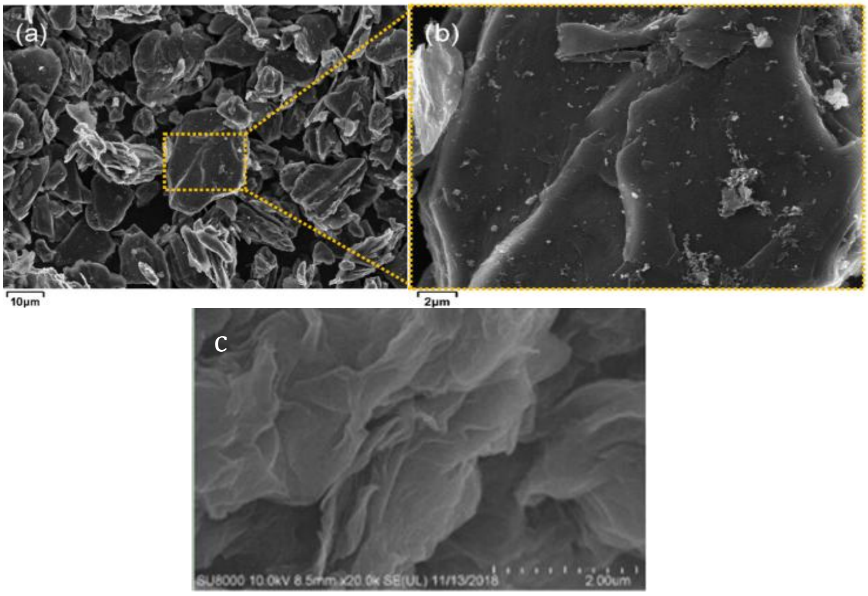


Fig. 2. (a–b) SEM images showing the surface morphology of regenerated graphene through acid–alkali treatment; (c) Graphene oxide synthesized via the Hummers method (Ji et al., 2024; Li et al., 2020; Li et al., 2022; Yi et al., 2021; Yu et al., 2021).

The refinement of surface morphology and structural order is anticipated to lower internal resistance, enlarge the electrochemically active surface area, and facilitate more efficient lithium-ion diffusion and intercalation during battery operation. These results are in agreement with prior studies such as that by Zhang et al. (2024), which confirmed that a combination of alkaline autoclaving and acid leaching effectively eliminates non-carbon impurities while maintaining the integrity of the graphite lattice. Similarly, Liu et al. (2024a) demonstrated that this regeneration strategy could achieve graphite purity above 99.9% with minimal structural degradation. Taken together, these findings validate that the alkali-acid method is an effective approach for regenerating graphene by removing contaminant compounds and enhancing surface characteristics. This method not only restores the functional properties of graphene for reuse in lithium-ion battery electrodes-especially in high-performance systems requiring extended cycle life and thermal stability-but also supports sustainable material recovery and circular economy practices in energy storage technology.

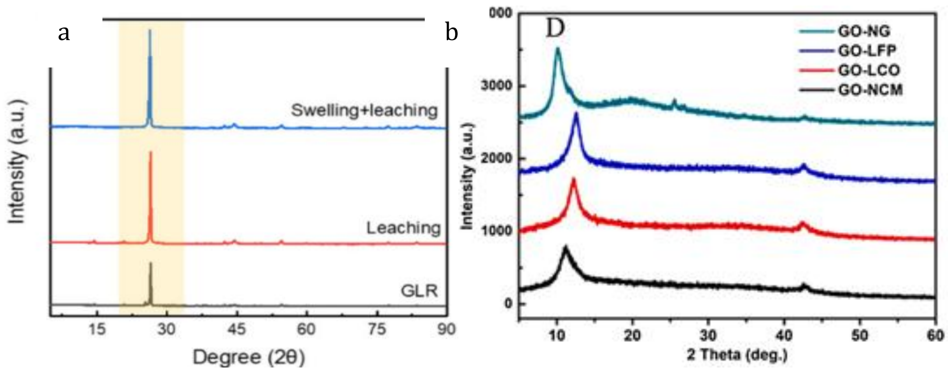


Fig. 3. (a) XRD patterns before and after impurity removal using acid–alkali treatment; (b) Transition from graphene to graphene oxide (GO) via the Hummers method (Ji et al., 2024; Li et al., 2022; Yi et al., 2021; Yu et al., 2021).

X-ray Diffraction (XRD) analysis was conducted to examine the changes in crystal structure and crystallinity of graphene before and after the regeneration process. As shown in Figure 3(a), the diffraction pattern indicates that following the impurity removal process, the intensity of the peak corresponding to the (002) crystal plane increases, signifying an enhancement in graphene crystallinity. Additionally, a shift of this peak towards a higher 2θ angle is observed, indicating reduced interlayer spacing and a structure more similar to that of commercial graphene. This narrowing of interlayer distance suggests improved π–π stacking interactions between graphene layers, which is favorable for electronic conductivity in battery applications. Figure 3(b) further supports this with a clearer and sharper (002) reflection, characteristic of purified and ordered graphitic structures.

Meanwhile, Figure 3(c) presents the morphology of regenerated graphene prepared using the Hummers method, where the oxidation process not only removes impurities but also expands the layered structure into graphene oxide (GO) sheets. This structural transformation is confirmed by the XRD pattern in Figure 3(b), where the main peak at 2θ ≈ 26.5° disappears and is replaced by a new broad peak at approximately 10–12°, corresponding to the (001) plane of GO. The emergence of this GO peak indicates an increase in interlayer spacing due to the insertion of oxygen-containing functional groups, reflecting successful oxidation and exfoliation into graphene oxide. These results align with the findings of Kanbur et al. (2024), who reported the appearance of the GO (001) peak at ~10°, and Sun et al. (2024), who showed that graphene crystallinity enhancement can be tracked by the intensification of the (002) peak after ultrasonic exfoliation.

The Hummers method, widely adopted for GO synthesis, uses aggressive oxidizing agents such as $KMnO_4$ and H_2SO_4, which can damage the carbon lattice due to their non-selective reactivity. In contrast, the alkali-acid method offers a milder and more targeted approach to impurity removal, preserving the crystalline integrity of the graphene structure. This process involves alkaline treatment followed by acid leaching, allowing selective dissolution of embedded mineral impurities. A study by Zhang et al. (2023b) demonstrated that this method successfully increased graphite purity from 93.09% to 98.45% by removing specific contaminants such as SiO_2, Al_2O_3, and Fe_2O_3 through controlled chemical pathways. Therefore, while the Hummers method is useful for GO production, the alkali-acid route is more suitable for regenerating conductive, crystalline graphene intended for electrochemical applications.

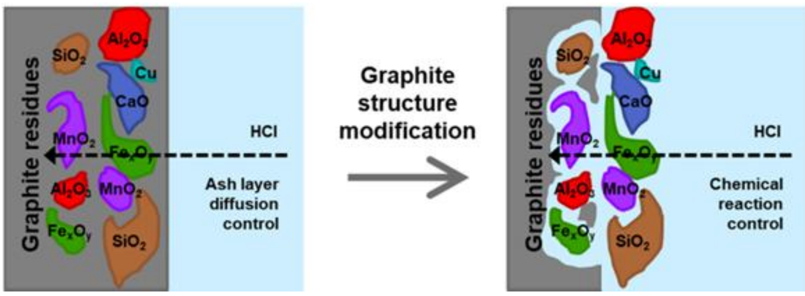


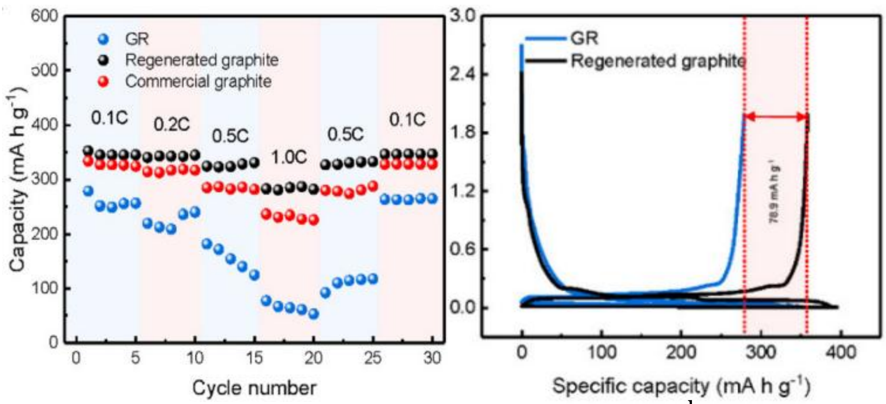
Fig. 4. Mechanism of the leaching process before and after structural modification of graphene residue (GR) using the acid–alkali method (Ji et al., 2024; Li et al., 2022).

The graphene structure undergoes swelling after alkali treatment, leading to the formation of new pores and an increased interlayer spacing. This expansion occurs as hydroxide ions interact with oxygen-containing functional groups and defect sites, disrupting van der Waals forces between graphene layers. This morphological change facilitates the penetration of leaching agents, such as hydrochloric acid (HCl), into the internal structure of graphene, allowing direct interaction with impurity phases without significant barriers. As a result, the leaching efficiency is significantly enhanced, enabling more effective removal of contaminant compounds such as Al_2O_3, SiO_2, and Fe_2O_3.

The alkali-induced swelling also promotes the diffusion of protons and complexing agents into deeper regions of the graphite matrix, where conventional surface leaching would be less effective. Zhang et al. (2023b) reported that this swelling mechanism plays a crucial role in opening diffusion pathways for the acid solution into the graphite microstructure, thereby improving the overall purification efficiency from 93.09% to 98.45% in the waste graphite regeneration process. These findings suggest that the synergistic effect of structural expansion and selective leaching enhances the accessibility of internal impurity phases, offering a more efficient and less destructive alternative to oxidative purification methods.

3.1.2 Electrochemical testing

Electrochemical tests using Cyclic Voltammetry (CV) and Galvanostatic Charge–Discharge (GCD) were conducted to evaluate the redox characteristics, electrochemical stability, and conductivity of graphene before and after regeneration. The test results are as follows:



a b

Fig. 5. (a) Rate performance test using cyclic voltammetry (CV) comparing regenerated graphene, used graphene, and commercial graphene; (b) Galvanostatic charge–discharge (GCD) test results (Ji et al., 2024; Li et al., 2022).

Figure 5(a) shows the rate capability test results, indicating that the regenerated graphene maintains a stable specific capacity across various current rates ranging from 0.1C to 1C. This behavior demonstrates that the regenerated graphene possesses good electrical conductivity and a stable internal structure, even under increasing charge–discharge rates. In contrast, spent graphene exhibits a significant drop in capacity at higher current rates, reflecting its inability to sustain electrochemical performance under elevated loads due to structural degradation and residual impurities. The nearly identical performance between regenerated and commercial graphene confirms the effectiveness of the purification and structural restoration process.

Furthermore, Figure 5(b) presents the galvanostatic charge–discharge (GCD) curves, illustrating the voltage–capacity relationship during charging and discharging cycles. The regenerated graphene displays GCD curves with symmetric profiles and moderate voltage plateaus, closely resembling those of commercial graphene. This indicates good reversibility of lithium-ion intercalation/deintercalation and minimal polarization, which are signs of low internal resistance and high Coulombic efficiency. Conversely, the GCD curve of the spent graphene is less stable, showing a sharper voltage drop and an asymmetrical profile, suggesting higher internal resistance and reduced energy storage efficiency. These findings are supported by the study of Zhang et al. (2023b), which reported that regenerated graphene recovered from spent battery anodes exhibits electrochemical performance approaching that of commercial graphene, with stable specific capacities across varying current rates and GCD profiles indicative of efficient charge–discharge cycling. Thus, the electrochemical data confirm that regenerated graphene not only regains its structural and chemical integrity but also performs reliably under dynamic operating conditions, making it a viable candidate for reuse in lithium-ion batteries.

3.2 Characterization and testing results of nmc cathode

3.2.1 Morphological analysis

The results of the Scanning Electron Microscope (SEM) analysis revealed significant morphological changes in the NMC cathode material ($LiNi_{1}/_{3}Mn_{1}/_{3}Co_{1}/_{3}O_{2}$) before and after battery cycling, as well as after regeneration using the molten salt method. The pristine NMC, shown in Figure 6(a), exhibits a typical spherical particle morphology with smooth and dense surfaces, indicative of well-sintered and uniform crystalline grains. However, after repeated charge–discharge cycles, as illustrated in Figures 6(b) and 6(c), the NMC structure undergoes substantial degradation, including surface roughening, the emergence of irregular pores, and the formation of large intergranular cracks. These features indicate mechanical and chemical stress induced by lithium-ion intercalation/deintercalation, leading to particle fracture and structural instability. Such damage compromises the electrode's electrochemical reversibility and contributes to capacity fading during long-term cycling.

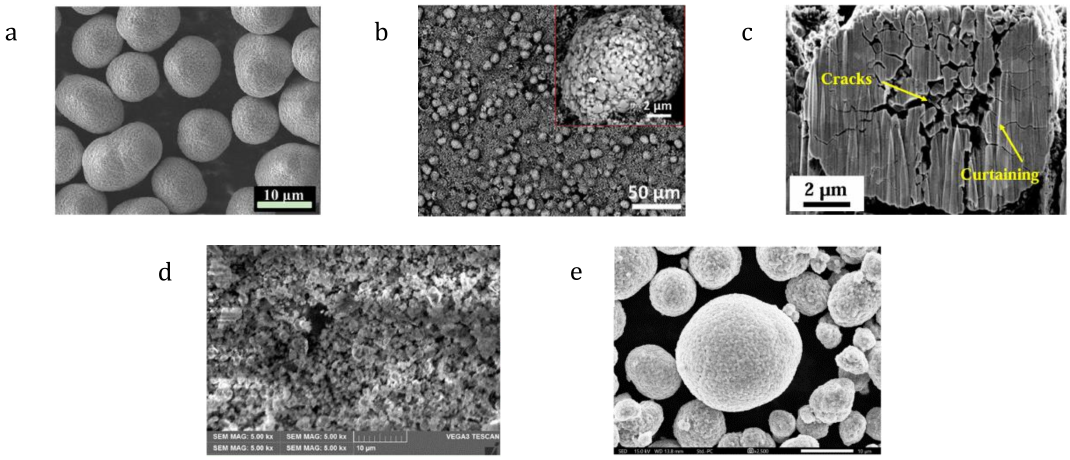
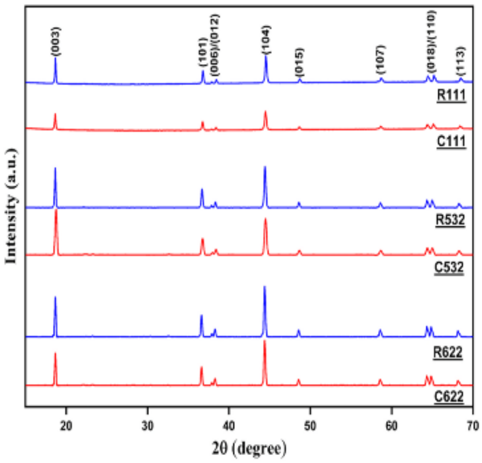


Fig. 6. SEM analysis of NMC material: (a) pristine NMC; (b–c) morphological changes after life cycles; (d–e) SEM images of regenerated NMC treated with molten salt (El Mounafia et al., 2023; El Moutchou et al., 2021; Jiao et al., 2018; Marchesini et al., 2022; Setyawati et al., 2024).

Regeneration using the molten salt method, as shown in Figures 6(d) and 6(e), effectively restores a more uniform and compact particle morphology that closely resembles the original state, although minor changes in surface texture remain. This regeneration technique utilizes high-temperature ionic diffusion and chemical reconstitution driven by molten salt interactions, which enable reformation of the damaged crystal lattice and partial healing of microstructural defects. As a result, both the mechanical integrity and electrochemical performance of the NMC material are enhanced. A study by Koong & Demopoulos (2024) demonstrated that molten salt-based calcination can yield single-crystal NMC particles with highly uniform morphology and improved cycling stability. Similarly, Shangguan et al. (2019) confirmed that this method not only repairs surface degradation but also improves the thermal stability and energy storage capacity of spent NMC cathodes. These findings validate the molten salt approach as an efficient route for restoring high-performance cathode materials, offering potential for sustainable recycling of lithium-ion battery components.

3.2.2 XRD analysis

The reaction mechanism in the cathode regeneration process using the low-temperature molten salt method, which employs ammonium sulfate ($(NH_4)_2SO_4$) and degraded lithium battery materials such as $LiNi_1/_3Mn_1/_3Co_1/_3O_2$, proceeds through multiple temperature-dependent stages, as illustrated in Figure 7(b). At elevated temperatures, ammonium sulfate thermally decomposes, releasing high-energy H^+ ions that break the metal–oxygen covalent bonds within the cathode's crystal lattice. This leads to the formation of metal sulfate compounds, as described by Zhu et al. (2014). The breakdown of these bonds creates a porous microstructure, which expands the active surface area and facilitates more efficient metal ion diffusion. Concurrently, the oxygen atoms liberated from the lattice react with hydrogen and ammonia-byproducts of NH_4^+ decomposition-to form water vapor as a secondary product, as noted by Tsukasaki et al. (2018). These gas-evolving reactions help dislodge residual impurities and promote ion transport pathways during re-sintering.



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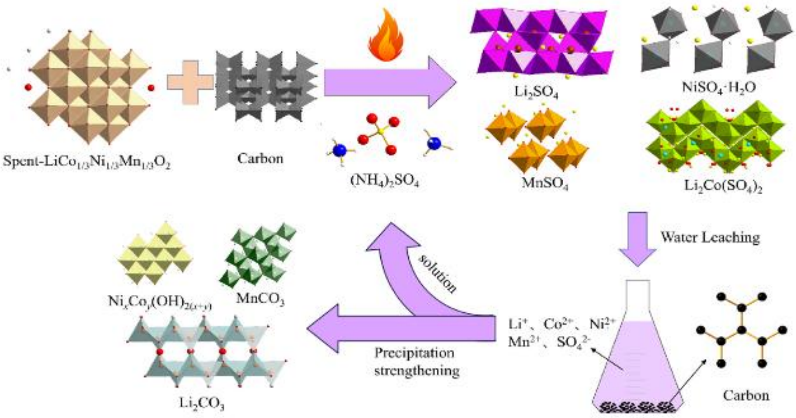


b

Fig. 7. XRD spectra of commercial and regenerated cathode materials; Reaction mechanism of NMC cathodes treated with low-temperature molten salt method
(El Mounafia et al., 2023; Liu et al., 2024b).

Crystal structure analysis using X-ray Diffraction (XRD), shown in Figure 7(a), confirms that the molten salt regeneration process successfully restores the characteristic rhombohedral layered structure of $LiNi_1/_3Mn_1/_3Co_1/_3O_2$ with high crystallinity. This layered structure is crucial for enabling reversible lithium-ion intercalation and deintercalation during battery operation (Yang et al., 2012). The well-preserved rhombohedral phase ensures structural stability under repeated cycling, contributing to enhanced specific capacity, improved energy efficiency, and longer battery lifespan. These structural and electrochemical improvements demonstrate that the low-temperature molten salt method is an effective strategy for restoring degraded cathode materials. Moreover, this process provides a scalable and sustainable route for closing the loop in lithium-ion battery production through efficient resource recovery and material reuse.

3.2.3 Electrochemical testing

Electrochemical testing using the Galvanostatic Charge–Discharge (GCD) method, as shown in Figure 8, reveals that the electrochemical performance of NMC (Nickel Manganese Cobalt) cathode materials varies significantly depending on their composition and regeneration treatment. The regenerated variants (R) consistently exhibit lower initial capacities and more rapid capacity fading compared to their corresponding calcined (C) variants. Specifically, the C622 variant displays the highest initial specific capacity of 180 mAh g^{-1}, which decreases to 160 mAh g^{-1} after 50 cycles, while the R622 counterpart drops from 140 mAh g^{-1} to 120 mAh g^{-1} in the same period. A similar trend is observed in other compositions: C532 maintains a higher capacity (170 → 150 mAh g^{-1}) compared to R532, and C111 shows better retention (160 → 140 mAh g^{-1}) relative to R111. These results suggest that the calcination process improves structural integrity and restores lithium storage sites more effectively than direct regeneration methods.

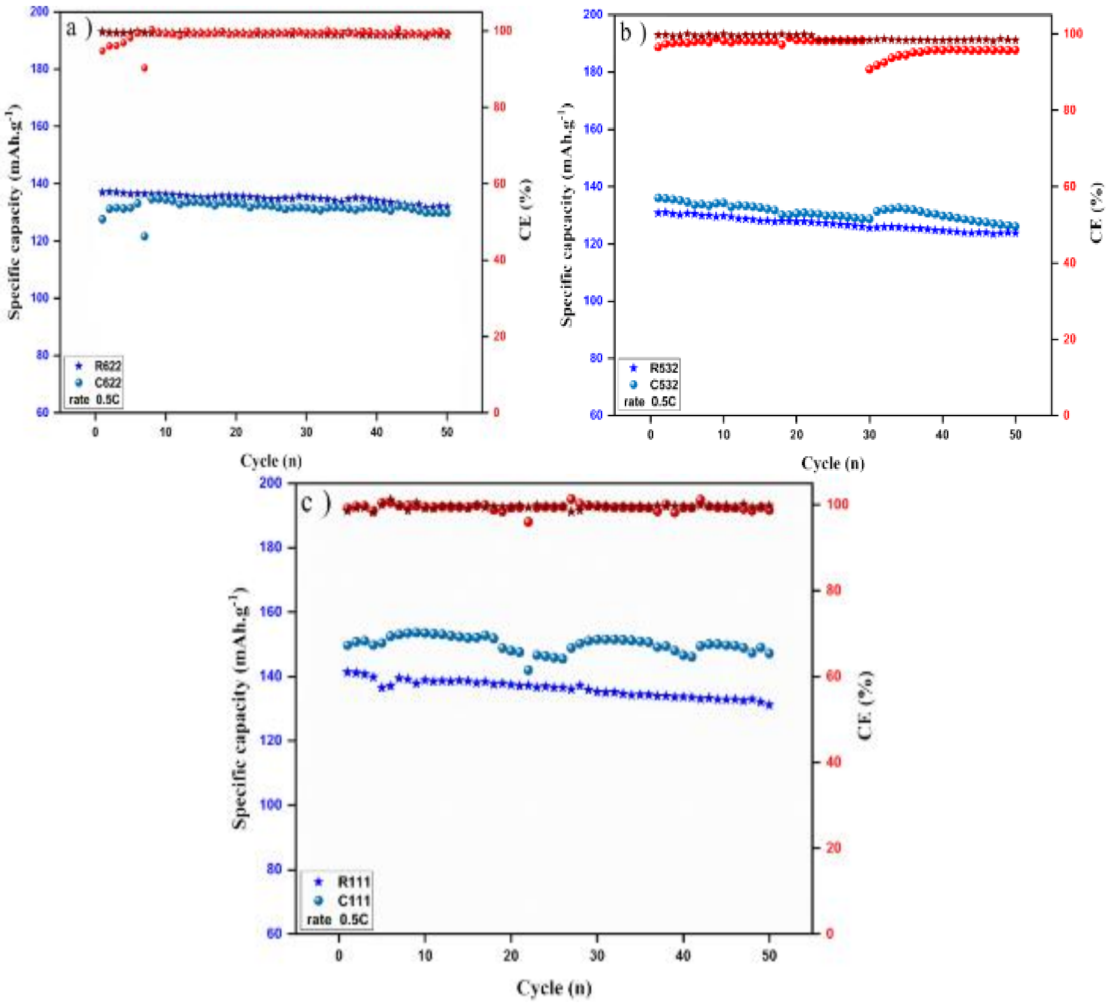


Fig. 8. Galvanostatic charge–discharge (GCD) comparison between regenerated and commercial NMC cathodes: (a) NMC622; (b) NMC532; (c) NMC111, at a rate of 0.5C (El Mounafia et al., 2023).

All tested samples exhibit a high and stable coulombic efficiency of approximately 99.5%, indicating that the charge–discharge processes are highly reversible and involve minimal parasitic reactions. This stable efficiency across cycles confirms the chemical stability of the regenerated and calcined NMC materials. Among the evaluated compositions, NMC622 stands out with the best overall electrochemical performance and the slowest rate of capacity degradation, indicating superior structural stability and lithium-ion kinetics. Therefore, it is considered a promising candidate for long-term lithium-ion battery cathodes. Future research should focus on further optimizing the crystalline phase stability, particle morphology, and surface chemistry of NMC622 to enhance its cycling durability and commercial viability (Hamed et al., 2024; Son et al., 2020).

3.3 Battery testing results of high-performance graphene and NMC/graphene

3.3.1 Morphological analysis

The integration of innovative electrodes combining regenerated graphene-based anodes and NMC/graphene composite cathodes demonstrates significant potential in enhancing lithium-ion battery performance. As shown in Figure 9(a), the regenerated graphene anode exhibits a smoother and more uniform surface, indicative of a well-structured, low-defect material suitable for rapid lithium-ion transport. Meanwhile, morphological analysis in Figure 9(b) reveals the successful formation of a thin, continuous graphene coating layer on the surface of NMC particles, which is further detailed in Figure 9(d). This coating serves as a conductive interfacial layer that envelops the cathode material, improving both electronic conductivity and interfacial contact with the electrolyte. The presence of this graphene layer is expected to facilitate more efficient charge transfer and enhance structural resilience during prolonged cycling. Prior research by Zhuang et al. (2020) supports this observation, showing that graphene-coated NMC cathodes exhibit enhanced electrode–electrolyte interface properties, improved conductivity, and reduced degradation under high-temperature or high-rate conditions.

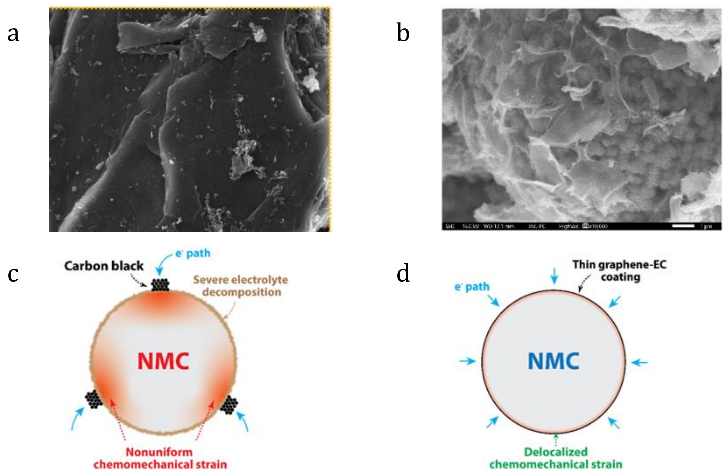
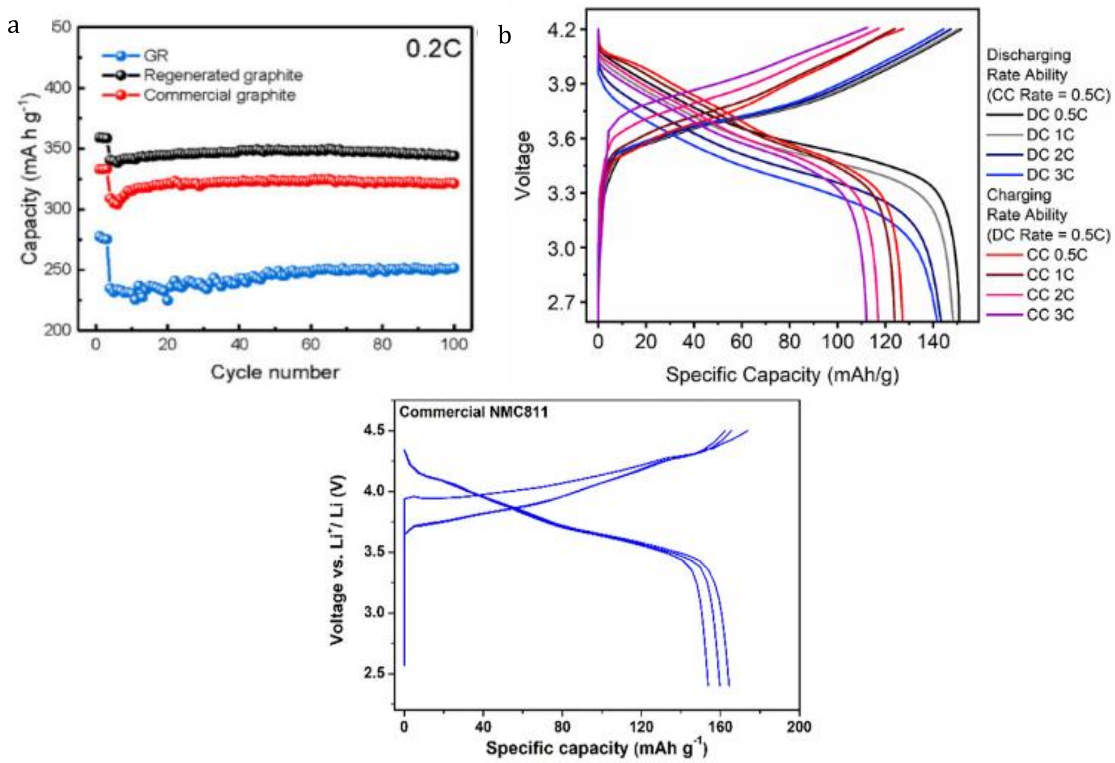


Fig. 9. (a) Regenerated graphene anode; (b) NMC/graphene composite cathode; (c) Uncoated NMC cathode; (d) Graphene-coated NMC cathode
(Li et al., 2022; Luu et al., 2021; Setyawati et al., 2024).

Figures 9(c) and 9(d) compare the charge transport mechanisms in uncoated versus graphene-coated NMC cathodes. In conventional uncoated systems, carbon black is typically used as a conductive additive. However, due to its dispersed nature and poor connectivity, this leads to non-uniform electron transport, resulting in localized electrolyte decomposition and uneven chemo-mechanical stress. These issues contribute to accelerated capacity fading and structural failure. In contrast, the graphene-coated NMC exhibits a more homogeneous current distribution, as the conductive graphene layer enables continuous and uniform electron flow across the cathode surface. This suppresses localized heating, reduces stress concentrations, and minimizes electrolyte breakdown, contributing to extended cycle life and improved safety. These findings align with the report by Hsu & Liu (2020), which demonstrated that graphene with optimized lateral size and surface coverage can effectively enhance conductivity pathways, preserve structural stability, and significantly prolong battery life in high-energy systems.

3.3.2 Electrochemical testing

Electrochemical testing was conducted by assembling the regenerated anode and composite cathode in a full-cell configuration to evaluate their combined performance before and after the regeneration process. The cyclic voltammetry (CV) analysis of the regenerated graphene anode, shown in Figure 10(a), revealed an initial specific capacity of 359 mAh/g and a capacity retention of 97.7% after 70 charge–discharge cycles. This excellent stability indicates that the regenerated graphene maintains its structural integrity and electrochemical activity under repeated cycling, attributed to the effective removal of impurities and the restoration of conductive pathways. In comparison, the used graphene (GR) anode exhibited significantly lower performance due to structural damage and residual contaminants from previous usage. Furthermore, these results outperform those of graphene synthesized via the Hummers method, which typically delivers 300–330 mAh/g, although still slightly below the performance of high-grade commercial graphene (Lee et al., 2021). This highlights the effectiveness of the alkali–acid regeneration process in restoring both structural and electrochemical functionality.



c

Fig. 10. (a) Cycling performance via CV analysis of the graphene anode; (b) NMC/graphene cathode; (c) Commercial NMC cathode (El Moutchou et al., 2021; Li et al., 2022; Setyawati et al., 2024).

Meanwhile, the integration of graphene into NMC-based cathodes yielded notable improvements in capacity and rate performance. As shown in Figure 10(b), the NMC/graphene composite cathode achieved a specific capacity of 158.1 mAh/g at a current rate of 0.5C, with a stable operating voltage centered around 3.7 V. In contrast, the uncoated NMC cathode in Figure 10(c) displayed reduced capacity and voltage stability, which can be attributed to increased internal resistance and slower lithium-ion transport. The graphene coating acts as a conductive network that bridges active material particles, enhances electron transport, and ensures more homogeneous charge distribution across the electrode surface. This modification not only reduces polarization but also supports sustained performance under high-rate conditions. Therefore, the dual application of graphene-as a regenerated anode material and as a cathode coating-demonstrates strong potential for deployment in 18650 cylindrical lithium-ion batteries, where improvements in specific capacity, rate capability, and production efficiency are critical for commercial viability (Zhuang et al., 2020).

3.4 Waste treatment in NMC graphene production

3.4.1 Waste processing data in NMC graphene production

The management of Nickel Manganese Cobalt (NMC)-based batteries, graphene, and lithium-ion battery waste in Indonesia has emerged as a critical issue amid the rapid growth of the electric vehicle (EV) industry. Companies such as PT Industri Baterai Indonesia (IBC) and Nanotech Energy have initiated technological developments to support battery production and recycling, including plans to establish a nickel-based EV battery recycling facility by 2031 as part of a national green industry strategy (Indonesia Business Post, 2023). Despite these advancements, the handling of spent lithium-ion batteries remains a pressing concern due to the presence of hazardous metals such as nickel and cobalt, which pose environmental and health risks if not properly managed. Globally, battery waste reached 180,000 tons in 2018 (Yu et al., 2021), and this number is expected to rise sharply with increasing EV adoption. Indonesia's strategic advantage lies in its vast mineral reserves, comprising 4.5 million tons of nickel (6.08% of global reserves), 484,461 tons of cobalt (6.85%), and 130 million tons of manganese (19.17%) (Fortune, 2025), positioning the country as a key player in the global battery supply chain.

However, Indonesia’s battery waste management system still faces significant challenges, including underdeveloped recycling infrastructure, high operational costs, and low public awareness regarding hazardous waste disposal. These limitations not only hinder resource recovery but also exacerbate environmental threats such as soil contamination, deforestation, and aquatic ecosystem damage resulting from mining expansion. To address these issues, the implementation of circular economy strategies is urgently needed, emphasizing the transformation of end-of-life batteries into secondary raw materials to close the resource loop and reduce dependency on primary extraction. According to Sonu et al. (2023), this approach can enhance industrial sustainability while mitigating environmental impacts. Moving forward, a coordinated effort involving government agencies, industry stakeholders, academia, and civil society is essential to strengthen policy frameworks, incentivize battery recycling technologies, and facilitate Indonesia’s transition toward a low-carbon economy. Such integrative measures will not only accelerate clean energy deployment but also reinforce Indonesia’s role as a sustainable hub in the global energy transition.

3.4.2 Regulations and waste treatment methods at industrial scale

The Indonesian government has introduced several regulatory frameworks to support lithium-ion battery (LIB) waste management and accelerate the national energy transition. The National Energy General Plan (RUEN) targets the deployment of 2.2 million electric two-wheelers and 2.1 million electric four-wheelers by 2030, alongside domestic battery industry development (Kementerian ESDM, 2017). Supporting this, Ministerial Regulation No. 50/2017 provides the legal basis for renewable energy expansion, while Presidential Regulation No. 55/2019 mandates that electric vehicle manufacturers are responsible for managing battery waste throughout the product lifecycle (Government of Indonesia, 2019). Furthermore, regulations issued in 2021 require the standardized handling of hazardous and toxic (B3) waste, including LIBs, through certified treatment and recycling facilities. The Ministry of Environment and Forestry also mandates manufacturers to establish sustainable waste treatment mechanisms, aligning national goals with circular economy principles (Kementerian Lingkungan Hidup dan Kehutanan, 2021).

Indonesia has also implemented 3R (Reduce, Reuse, Recycle) principles in several regulations, including Government Regulation No. 101/2014 on B3 waste and Ministerial Regulation No. P.75/2019 on producer waste reduction through product design and post-consumer waste management (Government of Indonesia, 2014; KLHK, 2019). However, despite this regulatory progress, the LIB waste sector still lacks a specific and comprehensive framework tailored to battery recycling technologies, logistics, and material recovery standards. In comparison, the United States enforces the Resource Conservation and Recovery Act (RCRA) and funds battery recycling research through the Infrastructure Investment and Jobs Act (2021). The European Union has launched the Battery Passport initiative to maximize traceability and metal recovery, while China has implemented an Extended Producer Responsibility (EPR) system and imposed a total ban on solid waste imports. Japan manages LIB recycling through a dedicated organization, the Japan Portable Battery Recycling Center (JBRC) (Bird et al., 2022; Kumar et al., 2021). These international models offer valuable references for Indonesia to develop an integrated, accountable, and forward-looking LIB regulatory framework.

To support these policy goals, the regeneration of graphene anodes using the alkali–acid method and NMC cathodes using the low-temperature molten salt method offers a viable and sustainable solution. These methods enable the reuse of spent electrode materials by restoring their electrochemical performance to near-commercial levels. By reducing the volume of hazardous B3 waste and minimizing reliance on virgin raw materials, these regeneration techniques align closely with circular economy objectives. Moreover, the environmental footprint of such methods is significantly lower than traditional disposal or smelting-based recycling. Encouraging local producers to adopt EPR mechanisms-similar to those implemented in the EU, China, and Japan-would enhance Indonesia's LIB waste governance and position the country as a regional leader in sustainable battery technology and resource recovery.

4. Conclusions

This study proposes an innovative strategy for lithium-ion battery (LIB) waste management through the regeneration of graphene-based anodes and Nickel Manganese Cobalt (NMC)-based cathodes using a combination of alkali–acid and low-temperature molten salt processes. The method significantly enhances electrode performance, with the regenerated anode achieving a specific capacity of 359 mAh/g and the cathode 158.1 mAh/g, both demonstrating high cycle stability comparable to commercial materials. In addition to being more environmentally friendly and energy-efficient than conventional hydrometallurgical or pyrometallurgical methods, this approach improves charge transfer efficiency, electron conductivity, and structural integrity of the electrodes. By enabling the recovery and reuse of high-value materials, the process supports circular economy principles, reduces dependency on primary metal mining, and lowers the volume of hazardous waste. With the support of national regulations and Indonesia’s abundant mineral reserves, this technology holds strong potential for industrial-scale application in remanufacturing 18650-type batteries, positioning Indonesia as a competitive and sustainable hub in the global battery supply chain.

Acknowledgement

Author would like to express my sincere gratitude to the editorial team and reviewers for their invaluable contributions to this work. The author also acknowledges those who helped in language editing, proofreading, and technical writing, which greatly enhanced the quality of this manuscript.

Author Contribution

The author is solely responsible for the entire process of this research and article preparation. The contributions include formulating the research idea, data collection, data analysis, interpretation of the results, writing the manuscript, and final revisions prior to publication.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The author declare no conflict of interest.

Open Access

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Biographies of Author

Jesaya Hansel, Department of Chemistry, Faculty of Science and Mathematics, Diponegoro University, Semarang, Central Java 50275, Indonesia

- Email: Jesayahansel97@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A