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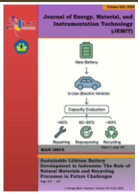

Sustainable Lithium Battery Development in Indonesia: The Role of Natural Materials and Recycling Processes in Future Challenges

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Abstract

The development of sustainable lithium-ion batteries is essential to meet the global demand for efficient, high-capacity, and environmentally friendly energy storage systems. This study reviews recent advancements in lithium battery technologies in Indonesia, emphasizing the utilization and performance of locally available natural materials. Among various lithium-ion battery types, those based on Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) are considered the most promising for Indonesia due to the availability of key raw materials such as nickel, cobalt, and iron. Additionally, various battery recycling techniques—including pyrometallurgy, hydrometallurgy, bio-hydrometallurgy, and direct recycling methods—are systematically analyzed for their effectiveness in material recovery and environmental impact mitigation. The findings highlight the need for integrated strategies that combine local material utilization, innovation in battery materials and recycling technologies, environmental stewardship, and supportive regulatory frameworks to accelerate the development of a sustainable lithium-ion battery ecosystem in Indonesia.

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Abstrak

Pengembangan baterai lithium-ion secara berkelanjutan sangat penting untuk memenuhi kebutuhan global akan sistem penyimpanan energi yang efisien, berkapasitas tinggi, dan ramah lingkungan. Studi ini mengulas kemajuan terbaru teknologi baterai lithium di Indonesia dengan fokus pada pemanfaatan dan kinerja bahan alam lokal yang tersedia. Di antara berbagai jenis baterai lithium-ion, baterai berbasis Lithium Nickel Manganese Cobalt Oxide (NMC) dan Lithium Iron Phosphate (LFP) dipandang paling potensial untuk dikembangkan di Indonesia karena ketersediaan sumber daya alam utama seperti nikel, kobalt, dan besi. Selain itu, berbagai teknik daur ulang baterai—termasuk pirometalurgi, hidrometalurgi, bio-hidrometalurgi, dan daur ulang langsung—ditinjau secara sistematis berdasarkan efektivitas pemulihan material dan dampaknya terhadap lingkungan. Temuan studi ini menekankan pentingnya strategi terpadu yang menggabungkan pemanfaatan bahan lokal, inovasi teknologi material dan daur ulang, kepedulian lingkungan, serta dukungan kebijakan untuk mempercepat pengembangan ekosistem baterai lithium-ion yang berkelanjutan di Indonesia.

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1. Introduction

Environmental concerns have accelerated the transition toward renewable energy and electrified transportation, significantly increasing the demand for efficient large-scale energy storage solutions such as batteries. The global battery market is projected to grow at a compound annual growth rate (CAGR) of 15.8% from 2023 to 2030, reaching an estimated value of USD 329.84 billion by 2030 (Jenis et al., 2024). Among various energy storage technologies, lithium-ion (Li-ion) batteries stand out due to their high energy density, long cycle life, reliability, and widespread adoption, making them the preferred choice for numerous applications worldwide (Hasan et al., 2025). This rapid growth underscores the importance for countries with strategic raw materials to position themselves competitively in the global battery market.

Indonesia, with its abundant strategic mineral reserves—particularly nickel, cobalt, and iron—has the potential to play a key role in the global battery value chain (Krustiyati & Gea, 2023)(Firmanto et al., 2024)(Pandyaswargo et al., 2021)(Latif et al., 2018). Nickel and cobalt are essential components for $LiNi_{1-x-y}Mn_xCo_yO_2$ (NMC) batteries, while iron is essential for $LiFePO_4$ (LFP) batteries. Nevertheless, the domestic lithium battery sector still faces challenges including technological constraints, reliance on imported raw materials, and environmental impacts associated with production processes and waste management. Aligning domestic capabilities with global trends requires continuous research and development (R&D), particularly in greener manufacturing processes and sustainable raw material utilization (Aflaki et al., 2021)(Bhattacharya & Goswami, 2020)(Hamid Nour et al., 2024).

To address these challenges, leveraging local natural resources and enhancing recycling processes emerge as critical strategies for establishing a more sustainable lithium battery industry in Indonesia (Murdock et al., 2021). The utilization of alternative raw materials from Indonesia's rich natural reserves could reduce import dependency while mitigating the environmental impact associated with extraction and processing. Efforts are needed to reduce carbon emissions in the energy sector energy sector through clean energy and the development of environmentally sustainable technologies (Olubunmi Bashiru et al., 2024). Additionally, lithium battery recycling provides an opportunity to reclaim valuable materials and reduce electronic waste, which poses substantial environmental risks. Therefore, various recycling techniques, such as pyrometallurgy, hydrometallurgy, and direct regeneration, must be evaluated systematically to identify the most economically feasible and environmentally friendly approach within the Indonesian context (Lim & Alorro, 2021).

Indonesia mineral wealth and strategic geographic position offer strong potential for the country to emerge as one of the leading producers of electric vehicle batteries globally, given its abundant mineral resources and strategic geographical position(Pandyaswargo et al., 2021)(Budiono & Virgianita, 2024)(Veza et al., 2022)(Pirmana et al., 2023). This review aims to present a comprehensive analysis of lithium battery development in Indonesia, focusing on the role of locally sourced natural materials, evaluation of current battery technologies, and assessment of various recycling approaches.

To ensure transparency and scientific rigor, this review adopts a structured literature review approach. Literature searches were conducted in Scopus, ScienceDirect, and Google Scholar using combinations of relevant keywords—such as "lithium battery," "Indonesia," "natural materials," "recycling," "$LiFePO_4$," and "NMC"—combined with Boolean operators (AND, OR). The primary search period covered publications from 2014 to 2025, while earlier studies prior to 2014—including works from 1994, 2012, and 2013—were retained as foundational references due to their historical, theoretical, or comparative significance in battery research. In addition to studies directly addressing lithium batteries in the Indonesian context, supporting literature on battery recycling, cathode innovations, sustainable supply chains, and circular economy strategies was also included to provide broader context. Inclusion criteria comprised peer-reviewed journal articles, conference proceedings, and authoritative reports accessible in full text, while exclusion criteria removed non-scientific works and sources unrelated to battery technology or sustainability. From an initial pool of 115 publications, 91 were deemed relevant after screening—comprising 3 foundational references (<2014) and 88 recent studies—organized into three thematic domains: (1) cathode material advancements, (2) utilization of locally sourced natural materials, and (3) recycling technologies and sustainability considerations.

2. Current State of Lithium Battery Development in Indonesia

Li-ion batteries have undergone substantial development since their conceptual introduction in the 1970s, pioneered by John B. Goodenough, whose groundbreaking work on cathode materials laid the foundation for modern lithium-ion technology (Hasan et al., 2025). Commercialization began in the early 1990s, most notably by Sony, which introduced Li-ion batteries for consumer electronics such as camcorders and mobile phones (Hasan et al., 2025)(Brandt, 1994). With energy densities ranging from 100–250 Wh/kg or 250- 650 Wh/L and efficiencies up to 98%, lithium-ion batteries have become essential in a wide range of applications, from portable electronics to large-scale energy storage systems (Tasneem et al., 2025). Today, several types of lithium-ion batteries are widely used, Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Titanate (LTO), NMC, and LFP, each offering distinct trade-offs in terms of energy density, thermal stability, cycle life, and cost. A comparative summary of these battery chemistries and their respective characteristics is presented in **Table 1** (Koech et al., 2024).

Table 1. Comparison of cathode materials characteristics for Li-ion batteries.

Cathode Material (Formula)	Advantages	Limitations	Energy Density (Wh/kg)	Applications	References
LCO ($LiCoO_2$)	High capacity (~140–150 mAh/g), fast charging, excellent electronic conductivity	Expensive (cobalt), thermal instability, short lifespan	~540 (theoretical)	Smartphones, laptops, cameras	(Chen et al., 2024)(Krieger et al., 2013)
NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)	Long cycle life (>2000), high specific energy, good power capability	High cost, safety concerns due to cobalt content and thermal sensitivity	~250–300	EVs, energy storage, consumer electronics	(Z. Zhang et al., 2024)(Shan et al., 2021)
LFP ($LiFePO_4$)	Very safe, thermally and chemically stable, long cycle life, low cost	Lower energy density compared to LCO/NCA	90–160	EVs, grid storage, stationary systems	(Stallard et al., 2022)(Mauger & Julien, 2018)
LMO ($LiMn_2O_4$)	Cost-effective, non-toxic, high thermal tolerance, good rate capability	Capacity fading due to Mn^{3+} dissolution and Jahn–Teller distortion	~100–130	Hybrid vehicles, power tools	(Y. Huang et al., 2021)(Callegari et al., 2022)
NMC ($LiNi_xMn_yCo_{1-x-y}O_2$)	High specific energy, good thermal stability, reduced cobalt use	Cation mixing, transition metal dissolution, moderate cost	~200	EVs, energy storage, electronics	(R. Jung et al., 2019)(Tian et al., 2018)
Li-S (Li_2S_n)	High theoretical energy density, low-cost potential, lightweight	Polysulfide shuttle effect, poor cycle life	Up to 600	Aerospace, EVs (research phase)	(Y. Zhang et al., 2018)
Li-Air ($Li–O_2$)	Extremely high theoretical energy density, uses ambient O_2	Poor electrolyte stability, safety risks, expensive	~3505 (theoretical)	Future EVs, research-only	(Imanishi & Yamamoto, 2019)
Solid-State Li-ion	High energy density, dendrite suppression, excellent safety, long lifespan	High cost, still under development	~450	Next-gen EVs, portable electronics	(Moradi et al., 2023)(Jo et al., 2025)

Among all lithium-ion battery chemistries, Indonesia is clearly prioritizing the development of NMC types, primarily due to the country's abundant nickel reserves and the electrochemical advantages that nickel offers (Mubarok & Kartini, 2024)(Konewka et al., 2021). High-nickel NMC cathodes, such as NMC 622 and NMC 811, provide superior energy density and specific capacity, making them highly suitable for long-range electric vehicles (EVs) and grid-scale energy storage systems (Saaid et al., 2024). In line with this strategic focus, Indonesian researchers have actively advanced the synthesis and optimization of nickel-rich cathode materials.

Among the pioneering figures in this field are Evvy Kartini, founder of the National Battery Research Institute (NBRI) and senior researcher at National Research and Innovation Agency (BRIN), and Agus Purwanto, head of the Centre of Excellence for Electrical Energy Storage Technology at Universitas Sebelas Maret (UNS). Their respective teams have contributed substantially to developing NMC-based cathodes using various synthesis routes and performance improvement strategies.

Evvy Kartini and her team—including M. Fakhrudin, M. N. Fanani, and M. Purwamargapratala—have explored multiple synthesis techniques to improve material structure and electrochemical characteristics. Fanani et al. (2023) synthesized NMC-622 via oxalate co-precipitation, reporting enhanced crystallinity and capacity retention with a 60-minute reaction time (Fanani et al., 2023). Purwamargapratala et al. (2023) optimized sol–gel synthesis of NMC-541, identifying ideal precursor ratios to produce uniform morphology and stable phase formation (Purwamargapratala et al., 2023). Fakhrudin *et al.* (2024) later demonstrated the benefit of CeO_2 surface coating on NMC-811, showing improved rate performance and cycle stability (Fakhrudin et al., 2024).

Simultaneously, Agus Purwanto and colleagues at UNS have focused on scale-up and structural optimization of NMC cathodes to support industrial applications. An early study by Rahmawati et al. (2021) addressed the challenges of consistent mass production for NMC materials, emphasizing critical process control parameters(Rahmawati et al., 2021). Dyartanti et al. (2024) investigated the impact of electrode thickness and calendering on NMC-811, determining that a ~200 µm thickness yielded superior electrochemical performance (Dyartanti et al., 2024). Most recently, Purwanto et al. (2024) demonstrated pilot-scale synthesis of nickel-rich cathodes with optimized pH, temperature, and residence time, resulting in highly uniform products suitable for industrial deployment(Purwanto et al., 2024).

While NMC remains a strategic priority in Indonesia—driven by the country's substantial nickel resources and its compatibility with high-energy-density applications—global market dynamics increasingly favor Lithium Iron Phosphate (LFP) chemistry for its safety, thermal stability, and cost-effectiveness. As reported by Evro et al. (2024), both LFP and NMC battery prices have declined steadily from 2015 to 2023, but LFP experienced a much sharper price drop. In 2015, the price of LFP batteries was approximately USD 600/kWh, while NMC batteries were nearly USD 800/kWh, due in part to the high cost of cobalt and nickel used in their production (Evro et al., 2024)). By 2023, the price of NMC batteries had fallen to about USD 440/kWh, while LFP had decreased even further, narrowing the price gap between the two chemistries to around USD 150/kWh. This sharp decline in LFP pricing is attributed to the greater availability of low-cost raw materials and production scale-up, particularly from Chinese manufacturers. As a result, LFP is becoming increasingly competitive in cost-sensitive applications such as budget EVs and stationary energy storage systems, whereas NMC continues to dominate high-performance markets due to its superior energy density (Evro et al., 2024).

Although Indonesia's national strategy emphasizes the development of NMC batteries due to its abundant nickel resources, several Indonesian researchers have also made notable contributions to the advancement of $LiFePO_4$ (LFP) cathode materials. Early work by Lukman Noerochim and team (2014) demonstrated that hydrothermal synthesis temperature significantly affects the phase purity and electrochemical performance of LFP (Waluyo et al., 2014). In a related study, they also showed that carbon coating using sucrose precursors can effectively enhance the conductivity and cycling stability of LFP in aqueous electrolyte systems(Noerochim et al., 2016).

Building upon this foundation, Mochamad Zainuri and team have further advanced the development of LFP/C composites by exploring silicon doping and other structural modifications to improve electrochemical characteristics (Astuti et al., 2021). Their research also includes the use of Fe K-edge X-ray absorption spectroscopy to investigate the electronic structure and oxidation states of iron within the LFP lattice, providing deeper insight into its redox behavior and stability (Astuti et al., 2023).

The work of these research groups reflects a growing engagement with LFP technology in Indonesia. Their efforts signify not only progress in materials design and characterization, but also broader momentum in strengthening the country's capacity for lithium battery innovation beyond NMC-based systems. As this research landscape continues to evolve, increasing attention is also being directed toward the use of naturally abundant local resources as alternative raw materials for lithium battery components—an approach that holds significant promise for enhancing sustainability and reducing dependence on imported materials.

3. Role of Natural Materials in Lithium Battery Development

The development of lithium batteries has traditionally relied on commercial raw materials, with limited research focusing on naturally derived alternatives (Firdausi et al., 2020)(Angela et al., 2017). However, growing global emphasis on sustainability has spurred interest in the exploration of natural resources, especially in regions with abundant mineral deposits. Indonesia, endowed with rich reserves of nickel, cobalt, and iron, offers a unique opportunity to foster a sustainable lithium battery industry(Pandyaswargo et al., 2021) (Ravi et al., 2024) (Barman et al., 2022).

Natural materials present several advantages for lithium battery development. Most notably, they can reduce dependence on imported raw materials, a critical factor for nations like Indonesia striving to establish a resilient and self-sufficient battery ecosystem. Utilizing locally sourced materials not only supports domestic industry but also contributes to carbon footprint reduction by minimizing emissions from long-distance transportation and extraction processes (Abdallah et al., 2012) (M. Yang et al., 2023).

Researchers in Indonesia have actively investigated the potential of these natural resources. Locally sourced nickel and cobalt have been shown to perform effectively in the synthesis of Nickel Manganese Cobalt (NMC) cathodes (Pandyaswargo et al., 2021). These materials demonstrate electrochemical properties comparable to their commercial counterparts, reinforcing their viability for industrial-scale production (K. J. Huang et al., 2021). Iron, which is widely available across Indonesia, has become a cornerstone in the development of Lithium Iron Phosphate (LFP) batteries. Renowned for their safety, cost-effectiveness, and long cycle life, LFP batteries are particularly suitable for electric vehicles and stationary energy storage systems, providing a complementary solution alongside NMC technologies (Wen et al., 2020) (Jyoti et al., 2021). Furthermore, the potential of Indonesia's natural resources for iron raw materials has also been studied, particularly focusing on ironstone deposits such as those found in Tanah Laut, South Kalimantan (Angela et al., 2017).

Significant progress has been made in developing lithium batteries using natural ironstone as a source of iron for LFP batteries (Angela et al., 2017). Over the past five years, the performance and stability of these batteries have been significantly enhanced (Latif et al., 2022). Notably, methods to synthesize LFP using a dissolution method have been pioneered, showing promise in improving the electrical characteristics of the batteries (Latif et al., 2021). Additionally, the integration of reduced graphene oxide (rGO) derived from coconut shell waste has been explored as a conductive additive in LFP systems. Coating LFP particles with rGO has proven effective in enhancing electrical conductivity, thereby improving battery efficiency and stability (Omar et al., 2022).

In summary, the utilization of natural materials is integral in advancing sustainable lithium battery technology (Larcher & Tarascon, 2015). By leveraging domestic mineral resources, Indonesia can simultaneously address environmental concerns and reduce economic dependency on imported inputs. Continued innovation and research into locally sourced materials and their processing techniques are essential to unlock the full potential of these materials and position Indonesia as a competitive player in the global battery market (Amici et al., 2022) (Z. Yang et al., 2022).

4. Recycling Processes for Lithium Batteries

The recycling of lithium-ion batteries (LIBs) is a critical component of sustainable development, particularly in countries like Indonesia where the demand for electronic devices and electric vehicles is rapidly increasing. Effective recycling processes not only mitigate environmental pollution but also conserve valuable resources such as lithium, cobalt, and nickel (Asadi Dalini et al., 2020) (Du et al., 2022) (Yu et al., 2022). Various recycling methods have been developed, each with its own set of advantages and disadvantages. This section reviews the primary recycling methods, including direct recycling, pyrometallurgy, hydrometallurgy, bio-hydrometallurgy, and electrometallurgy, evaluating their respective processes, economic implications, recovery efficiencies, and potential applicability within the Indonesian context (Baum et al., 2022) (Gerold et al., 2024) (Shamsuddin, 2021).

In practice, the approach to handling end-of-life LIBs depends largely on their remaining capacity. Batteries with more than 80% of their original capacity can often be repaired or reconditioned for continued use in power-demanding applications—though this falls outside the strict definition of recycling. When the remaining capacity lies between 60% and 80%, batteries are typically repurposed for applications with lower power requirements, such as stationary energy storage. True recycling occurs when the capacity drops below 60%, at which point the battery is dismantled and its valuable components—such as lithium, nickel, cobalt, and iron—are extracted and reused in new battery production. This recycling classification based on remaining capacity—repair (>80%), repurpose (60–80%), and recycle (<60%)—is illustrated in **Figure 1** (Lan et al., 2025). Recent years have seen increasing interest from both academia and industry in refining these recycling pathways, with notable focus on hydrometallurgical recovery, direct regeneration, and lithium-specific extraction methods. These advancements are vital for establishing a circular battery economy and supporting Indonesia's long-term sustainability goals.

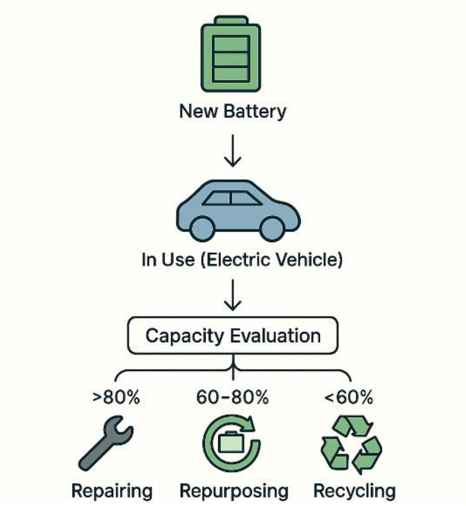

Figure 1. Recycling Classification based on remaining capacity

Direct recycling involves recovering battery components without chemically decomposing them into elemental forms, preserving the cathode material structure for reuse in new batteries (Islam & Iyer-Raniga, 2022). The process typically includes disassembling the battery, separating the components, and rejuvenating the active materials. The main advantage of direct recycling is its potential for high material recovery efficiency and lower energy consumption compared to other methods. However, it requires precise control over the battery disassembly process and the quality of the recovered materials can vary, which may affect the performance of the new batteries. The best results from direct recycling have shown recovery efficiencies of up to 95% for cathode materials, significantly reducing the need for new raw materials (Duan et al., 2021). Economically, direct recycling can be cost-effective due to lower energy requirements and the potential for high recovery rates. However, the initial setup costs for precise disassembly and rejuvenation processes can be high. The variability in the quality of recovered materials can also impact the economic viability, as inconsistent material quality may lead to additional processing costs. For instance, the cost of direct recycling is estimated to be around $1,500 per ton of batteries processed, with potential savings of up to 30% compared to new material production (Thompson, 2023).

Pyrometallurgy is a high-temperature process that involves smelting the batteries to separate valuable metals such as lithium, cobalt, and nickel. The process includes heating the batteries in a furnace, where the high temperatures cause the metals to melt and separate based on their different melting points. This method is well-established and can handle large volumes of batteries. The advantages of pyrometallurgy include its ability to process mixed battery chemistries and its robustness (Reinhart et al., 2023) (Windisch-Kern et al., 2022). However, it is energy-intensive and can produce significant greenhouse gas emissions. Additionally, the high temperatures can lead to the loss of some valuable materials and the formation of slag, which requires further processing. The best results from pyrometallurgy have achieved recovery rates of over 90% for cobalt and nickel, but with some loss of lithium (Leal et al., 2023). From an economic perspective, pyrometallurgy is capital-intensive due to the high energy requirements and the need for specialized equipment. The operational costs are also high, primarily due to energy consumption. However, the ability to process large volumes and mixed chemistries can offset some of these costs, making it economically viable for large-scale operations.

Hydrometallurgy uses aqueous solutions to leach metals from the battery materials. This method typically involves several steps, including leaching, solvent extraction, and precipitation (Larouche et al., 2020)(J. C. Y. Jung et al., 2021). The batteries are first shredded, and the resulting material is treated with acids to dissolve the metals. The metal-rich solution is then processed to selectively recover the desired metals (Saleem et al., 2023) (Tang et al., 2021). Hydrometallurgy is known for its high recovery rates and lower energy requirements compared to pyrometallurgy. It also allows for selective recovery of specific metals, which can be advantageous for producing high-purity materials. However, the process generates liquid waste that must be treated, and the use of strong acids and bases can pose environmental and safety risks. The best results from hydrometallurgy have shown recovery efficiencies of up to 98% for lithium, cobalt, and nickel (Asadi Dalini et al., 2020). Economically, hydrometallurgy is generally more cost-effective than pyrometallurgy due to lower energy consumption and the ability to achieve high recovery rates. The costs associated with waste treatment and the use of chemicals can be significant, but these are often outweighed by the high value of the recovered metals.

Bio-hydrometallurgy, or bioleaching, employs microorganisms to leach metals from battery materials (Christopher et al., 2025). This method involves using bacteria or fungi to produce organic acids that dissolve the metals from the battery components. The process is environmentally friendly and can operate at ambient temperatures, reducing energy consumption. Bioleaching is particularly effective for recovering metals from low-grade ores and waste materials. However, the process is generally slower than traditional hydrometallurgy and requires careful control of biological conditions to maintain the activity of the microorganisms (Nkuna et al., 2022). Additionally, the scalability of bioleaching for industrial applications remains a challenge. Economicaslly, bioleaching can be cost-effective due to its low energy requirements and the use of naturally occurring microorganisms. However, the slower processing times and the need for precise biological control can increase operational costs.

Electrometallurgy involves the use of electrical energy to recover metals from battery materials through processes such as electrolysis (Rai et al., 2021). In this method, the battery materials are dissolved in an electrolyte solution, and an electric current is applied to separate the metals. This method can achieve high-purity metal recovery and is relatively energy-efficient (Ill, 2023). Electrometallurgy is also versatile, allowing for the recovery of a wide range of metals. However, it requires significant capital investment in specialized equipment and infrastructure. The process also generates waste products that need to be managed properly to avoid environmental contamination. Economically, electrometallurgy can be advantageous due to its high recovery efficiencies and relatively low energy consumption (Rai et al., 2021). However, the high initial capital costs for equipment and infrastructure can be a barrier to entry. The ongoing operational costs, including electricity and waste management, also need to be considered. Despite these challenges, the high purity of recovered metals can provide significant economic returns.

Nevertheless, the economic aspect of lithium-ion battery recycling remains a major barrier to its large-scale implementation. The recycling system for electric vehicle batteries involves a comprehensive value chain encompassing collection, transportation, disassembly, and processing through three primary approaches—pyrometallurgical, hydrometallurgical, and direct recycling. Disassembly costs per kilowatt-hour (kWh) for the Tesla Model S battery vary significantly by location, estimated at $0.25 in China, $0.84 in South Korea, $1.68 in the United States, $4.04 in Belgium, and $2.84 in the United Kingdom. Meanwhile, international transportation costs are also substantial, reaching up to $28.02/kWh for shipments from the UK to China, contributing as much as 70% of the total recycling cost. The recycling process itself accounts for 75–90% of the overall cost, with pyrometallurgical methods being the most expensive and hydrometallurgical processes the most cost-efficient. The estimated Net Recycling Cost/Profit ranges from −$21.43 to +$21.91 per kWh, indicating that profitability is only achievable under specific conditions, such as direct recycling of NCA-based batteries in China. High labor costs and the complexity of battery pack design are identified as key barriers to manual disassembly, further emphasizing that automation of recycling processes has the potential to significantly reduce operational costs and improve overall efficiency (Lander et al., 2021)(Harper et al., 2019).

A summary and comparison of these methods, along with their advantages, disadvantages, and industrial maturity, are presented in **Table 2**. Understanding these recycling technologies and their economic implications can inform strategic decisions to optimize lithium-ion battery recycling in Indonesia, facilitating the development of a sustainable and economically viable circular battery economy (Yu et al., 2022) (Srinivasan et al., 2025) (Lo Sardo et al., 2025) (Rehman et al., 2025) (Zanoletti et al., 2024) (Dobó et al., 2023).

Table 2. Various Lithium Battery Recycle Methods, Advantages, Disadvantages, and Status in the Industry

No	Method	Advantages	Disadvantages	Industrial Status
1	Pyrometallurgy	Mature and simple process; No need for presorting; Suitable for large scale	High energy consumption; High toxic gas emissions; Lithium & Mn often unrecovered	Widely implemented
2	Hydrometallurgy	High recovery rate; Pure products; Low energy; Low emissions	Complex process; High water waste; Hazardous chemical reagents	Becoming common in industry
3	Direct Recycling	Eco-friendly; Low energy; Preserves original materials; Minimal processing steps	No universal protocol; Chemical variation issues	Lab/early commercial scale
4	Biometallurgy	Eco-friendly; Low energy; Low GHG emissions	Slow processing time; Low recovery efficiency; Not industry-ready	Exploratory/lab stage
5	Mechanochemistry	Non-toxic, low-cost reagents; Simple operation (ambient temp & pressure)	Efficiency depends on reagents; Long processing times	Experimental/lab stage
6	Solvometallurgy (DES)	Green and inexpensive process; Non-flammable; Easy preparation; Low toxicity	Difficult industrial scaling; Low cathode/DES ratio	Not industrialized
7	Solvometallurgy (Ionic)	Low volatility; Customizable; Non-flammable	High cost; Not stable at large scale	Not industrialized

5. Future Challenges and Opportunities

Despite Indonesia's strength in natural raw materials such as nickel and manganese, the development of sustainable lithium batteries faces several challenges. A primary challenge involves ensuring sustainable and environmentally responsible mining and processing practices. Uncontrolled mining activities can lead to environmental degradation and biodiversity loss, emphasizing the need for stringent regulations and sustainable mining technologies. Additionally, although Indonesia has abundant raw material reserves, domestic capabilities in environmentally friendly and efficient battery processing technologies remain limited and require significant development and investment.

Another challenge is enhancing battery efficiency and safety. Although lithium-ion batteries have improved energy density, accelerating charging times and extending battery lifespan remain crucial areas for further development(Xu et al., 2023). Emerging technologies, including solid-state batteries and lithium-sulfur batteries, promise these enhancements but are still in the research and development phase. Moreover, Indonesia must establish a robust battery recycling infrastructure to manage increasing volumes of end-of-life batteries effectively. Achieving this requires substantial investment in advanced recycling technologies, facilities, and skilled human resources (Habiburrahman et al., 2025).

Conversely, Indonesia holds significant opportunities in the development of sustainable lithium batteries due to its rich mineral reserves. Leveraging its abundant nickel and manganese resources can decrease import dependency, enhance supply chain resilience, and support the production of environmentally sustainable and high-performance batteries. Recent studies indicate that domestically sourced materials exhibit comparable or superior performance, highlighting their potential for large-scale industrial applications. Furthermore, with targeted government policies, infrastructure improvements, and foreign investments, Indonesia can position itself as a strategic hub for global battery production, stimulating economic growth and creating employment opportunities (Konewka et al., 2021) (Lahadalia et al., 2024).

Another promising opportunity is the advancement of LFP battery technology. Although LFP batteries offer lower energy density than nickel-based counterparts, they are gaining popularity due to their lower cost, higher safety, and reduced environmental impact. These batteries do not contain costly or ethically controversial materials like cobalt, making them particularly attractive for sustainable battery production. By focusing strategically on LFP technology, Indonesia can sustainably utilize its extensive iron resources while minimizing the environmental impacts of battery manufacturing. Developing both synthesis and recycling processes for LFP batteries could form the cornerstone of a comprehensive, sustainable, and economically viable battery industry in Indonesia.

Additionally, improving recycling methods to become more efficient, economically viable, and environmentally friendly presents another significant opportunity. Recycling technologies such as hydrometallurgy and direct recycling offer high material recovery rates and reduced environmental impacts, helping Indonesia minimize battery waste and enhance resource sustainability. Moreover, developing a robust recycling industry will stimulate job creation, support local economic growth, and strengthen the domestic circular economy.

By effectively addressing these challenges and strategically capitalizing on available opportunities, Indonesia can play a pivotal role in sustainable lithium battery development, supporting the global clean energy transition and reducing the environmental impacts associated with battery production and disposal.

6. Conclusions

The sustainable development of lithium-ion batteries in Indonesia presents significant opportunities driven by abundant local natural materials, particularly nickel, cobalt, and iron. Advancements in cathode materials, such as NMC and LFP, have demonstrated promising electrochemical performance, thermal stability, and cycling durability, aligning well with the demands for high-efficiency and reliable energy storage applications. The utilization of naturally sourced minerals and innovative material processing methods, including surface modification, doping strategies, and structural optimization, is crucial to enhancing battery performance and sustainability.

Additionally, the establishment of advanced recycling techniques, such as pyrometallurgy, hydrometallurgy, bio-hydrometallurgy, and direct regeneration, provides significant potential for recovering critical battery materials and minimizing environmental impacts from electronic waste. Continued research into electrode material innovations, electrolyte stability, and cell design optimization will be pivotal for Indonesia to develop a robust lithium-ion battery technology base. Addressing current technical challenges, including energy density limitations, charging kinetics, and battery lifespan, remains essential. These targeted efforts will significantly contribute to the advancement of energy storage materials, positioning Indonesia as a key contributor to global battery technology innovations.

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Declaration of Assistive Technologies in The Writing Proccess

I declare that AI-powered tools were used to assist with grammar and clarity editing of this manuscript. The final content and intellectual contribution remain the sole responsibility of the authors.

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