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Evaluating sustainability: A review of recycling technologies of spent lithium-ion batteries

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Abstract---*The lithium-ion battery business has grown significantly over the last eight years, with lithium recycling playing an essential role in this expansion. The organizations rely on lithium, a key component of lithium-ion batteries, which is derived from natural minerals and brines. However, the sophisticated and energy-intensive procedures required for lithium extraction consume a substantial amount of energy. Lithium usage poured by 18% between 2018 and 2019, indicating the depletion is inevitable. This has led to the development of various lithium recycling methods, including pyrometallurgy, hydrometallurgy, and electrochemical extraction. Despite increased interest in lithium recycling, less than 1% of lithium is presently recycled. Lithium-ion batteries are classified into several varieties, including lithium carbonate, lithium hydroxide, lithium metal, butyl lithium, and lithium specialty batteries. The applications section focuses on their use in transferrable strategies, rechargeable cars, and grid-energy packing structures. This study concludes by emphasizing the accumulative petition for lithium-ion batteries as well as the need for improvements in enactment, affordability, and safety.*

Keywords---*Direct Reuse, Electrochemical Processes, Hydrometallurgical Recycling, Li-Ion Battery Disassembly, Lithium-Ion Battery, Pyrometallurgical Processes.*

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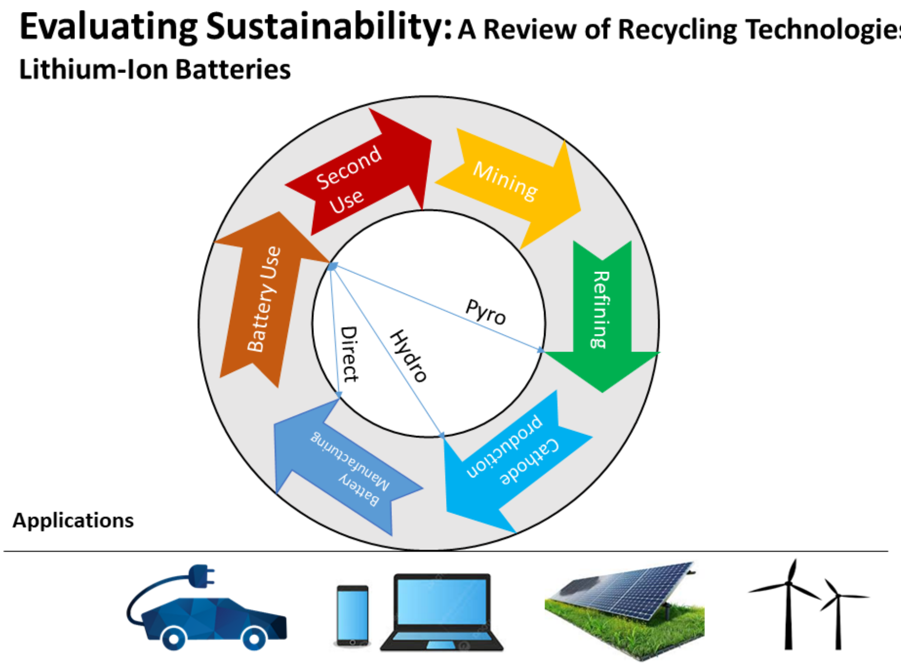


Introduction

In recent years, the field of energy research has been predominantly focused on discussions surrounding lithium-based technology. Since their first introduction to the market in 1991, lithium-ion batteries have emerged as a core liveliness equipment, undergoing continuous research and development over several decades to meet the demands of the upcoming vitality market (Tong et al., 2019). Lithium, a significant component of lithium-ion batteries, has garnered significant attention due to its unique properties. However, it is essential to note that lithium reserves are not uniformly distributed worldwide and are limited in their availability. Moreover, the rapid advancements in electrical vehicle (EV) and energy storage system (ESS) technologies have led to a substantial increase in the petition for lithium. Over the past decade, lithium consumption has more than doubled (Bae & Kim, 2021).

Due to the growing demand for lithium-ion batteries in various sectors, including electric vehicles and renewable energy storage, concerns about resource depletion and environmental impact have intensified. As a result, lithium recycling has emerged as a critical area of focus. Recycling lithium from waste lithium-ion batteries not only helps reduce the reliance on primary lithium sources but also diminishes the ecological footprint connected with cordless manufacture and removal. This review provides an overview of the technologies used for lithium recycling from waste lithium-ion batteries (Bernardes et al., 2004).

The recycling of lithium-ion batteries encompasses the withdrawal and recovery of valuable materials, primarily lithium, cobalt, and nickel, as well as other metals, from the battery waste. Various technologies have been developed and are currently being employed to achieve efficient and sustainable lithium recycling. These technologies encompass mechanical, hydrometallurgical, pyrometallurgical, direct cathode recycling, solvent extraction, supercritical fluid extraction, and membrane-based processes (Li et al., 2018). Mechanical shredding serves as the initial step in the recycling process, where waste lithium-ion batteries are shredded into smaller pieces, facilitating the subsequent separation of different components and materials. Hydrometallurgical processes involve the use of aqueous solutions to selectively dissolve and separate the metals present in the batteries. This can include techniques such as leaching, where the shredded batteries are immersed in a solution that dissolves the desired metals for further processing (Duan et al., 2022).

Pyrometallurgical processes utilize high-temperature operations, such as smelting, to melt and separate different metals based on their melting points. Direct cathode recycling is an emerging technology that focuses on the direct recovery of cathode ingredients, such as lithium, cobalt, and nickel, without dismantling batteries (Yang et al., 2021). This technique employs methods like direct electrorefining or selective dissolution to recover valuable materials from the cathodes (Sommerville et al., 2021). Solvent extraction and supercritical fluid extraction are alternative methods that leverage specific solvents or supercritical fluids to selectively extract lithium from the battery materials. These approaches offer efficient separation and purification of lithium for subsequent reuse (Li et al., 2019). Membrane technologies, on the other hand, employ selective membranes to allow the passage of lithium ions while blocking unwanted components, facilitating the concentration and recovery of lithium (Torkaman et al., 2017).

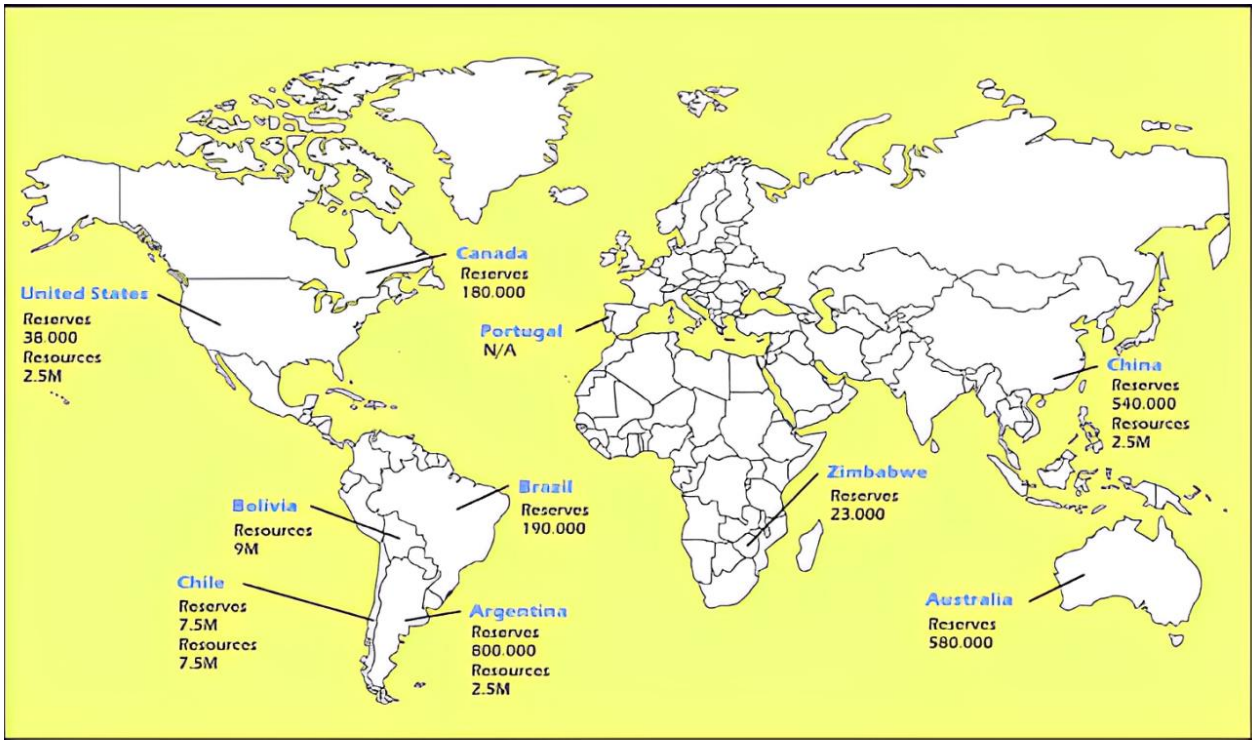


Figure 1: Overview of World lithium reserves and resources Ref. (Oliveira et al., 2015) © 2015 Elsevier Ltd

It is important to note that lithium recycling is a complex process, often involving a combination of different technologies to achieve optimal results in terms of efficiency and cost-effectiveness. The choice of a specific recycling method depends on various factors, including the battery's composition, desired product purity, and economic viability. Continued investigation and expansion hard work are incessantly refining existing technologies and also exploring novel approaches to heighten the productivity and sustainability of lithium reprocessing (Wang et al., 2022). Overall, the reprocessing of lithium from left-over lithium-ion batteries offers a noteworthy opportunity to establish a circular economy for battery materials, contributing to the conservation of resources and the reduction of environmental impact, as shown in Figure 1. Understanding and advancing the technologies for lithium recycling is essential for building a sustainable future in the rapidly growing battery industry (Chandran et al., 2021).

To the best of our knowledge, the purposes of lithium reprocessing from left-over lithium-ion batteries include resource conservation, reduction of environmental impact, proper management of hazardous materials, energy and cost savings, development of a circular economy, regulatory compliance, and fostering technological advancement and innovation. By recycling lithium and other valuable metals from batteries, resources are conserved, environmental impact is minimized, hazardous materials are safely managed, energy and costs are saved, and a circular economy for battery materials is promoted. Furthermore, lithium recycling helps meet regulatory requirements, drives technological advancements, and contributes to a sustainable and cleaner future.

History

The olden times of lithium-ion batteries date back to the 1970s when significant research and development efforts began to explore new energy storage technologies, as shown in Figure 2. Here's a summary of the key milestones and developments in the olden times of lithium-ion batteries: Lithium-ion battery research was initiated by M. In the 1970s, Stanley Whittingham employed lithium metal as the anode and titanium disulfide as the cathode. However, safety concerns concerning the custom of lithium metal limited its practical application. In the 1980s, John B.

Goodenough proposed using a lithium cobalt oxide cathode, which exhibited higher energy density compared to previous designs (Augustson & Reilly, 1974). In 1991, Sony Corporation commercialized the first rechargeable lithium-ion battery for consumer electronics, specifically camcorders. This breakthrough was made possible by incorporating a carbon-based material, graphite, as the anode instead of lithium metal, as mentioned in Figure 2. Sony's innovation made lithium-ion batteries lightweight, rechargeable, and safe for widespread use in portable electronic devices (Stetten et al., 1990).

Throughout the 1990s and 2000s, lithium-ion battery technology continued to evolve. Researchers concentrated on enlightening the energy density, cycle life, safety, and cost-effectiveness of lithium-ion batteries. Advancements included the development of new cathode materials like lithium manganese oxide (LMO), lithium iron phosphate (LiFePO4), and nickel-cobalt-aluminum (NCA) oxides, which offered higher performance and stability (Krehl & Takeuchi, 2000). With increasing concerns about fossil fuel consumption and climate change, the demand for high-capacity energy storage systems grew. Lithium-ion batteries have become a vital factor in electric vehicles (EVs) and renewable energy storage applications. Companies like Tesla Motors played a noteworthy part in driving the agreement of lithium-ion batteries for electric vehicles, leading to advancements in battery technology, cost reduction, and improved manufacturing scale (Tarascon, 2008).

The history of lithium-ion batteries was characterized by significant developments and milestones. This period witnessed the boom of electric vehicles (EVs) and the rise of Gigafactory for large-scale battery production. Lithium-ion batteries became crucial, aimed at grid-scale energy-loading organizations, supporting renewable energy integration. Researchers focused on material innovations to improve performance and safety while addressing concerns regarding cobalt supply and environmental impact (Lv et al., 2018). Safety concerns led to increased scrutiny and regulatory actions. Recycling and the establishment of a circular economy for battery materials have gained importance. Continued investigation and advanced determinations are aimed to augment energy density, cycle life, and safety, with solid-state batteries emerging as a potential next-generation technology. Overall, this period marked the expansion and continued evolution of lithium-ion batteries in various sectors (Natarajan et al., 2022).

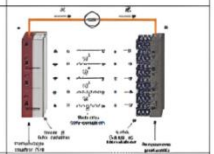
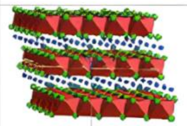
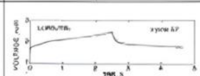
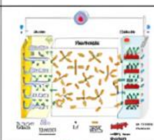
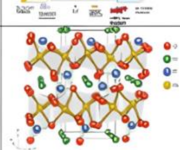
1972	Lithium primary battery Li/org elect CFx	Matsushita	
1972	Solid lithium iodine battery Li/LiI/I-PVP	Moser	
1977	Rechargeable lithium battery Li/ org elect/ TiS_2	Whittingham	
1978	Polymer electrolyte battery Li/PEO electr/V2O5	Armand	
1980	First lithium ion cathode LiCoO2	Goodenough	
1980	Rocking chair battery Li_xWO_2/org electr/TiS_2	Scrosati	
1991	Lithium ion battery C/org electr/$LiCoO_2$	Sony	
1997	Olivine type cathode, $LiFePO_4$	Goodenough	

Figure 2: A bird's eye view of the history of lithium batteries at a glance Ref. (Scrosati, 2011). Springer-Verlag 2011

In recent years, ongoing research efforts have concentrated on further enlightening the presentation and security of lithium-ion batteries. This includes exploring new materials, such as lithium- sulfur and lithium- air, to enhance energy density and cycle life. Additionally, efforts have been made to optimize battery manufacturing processes, improve battery management systems, and develop recycling technologies to discuss the end-of-life challenges connected with lithium-ion batteries. The evolution of lithium-ion battery technology continues, motivated by the growing petition for electric automobiles, grid energy storage, and moveable electronics. Investigators are discovering new resources, such as solid-state electrolytes, and substitute enterprises to boost energy compactness, protection, and sustainability, as mentioned in Table 1. Additionally, efforts are being made to develop next-generation battery technologies beyond lithium-ion, such as lithium-sulfur, lithium-air, and solid-state batteries, to encounter the cumulative energy storage sustenance of the future. The history of lithium-ion batteries spans several decades of scientific research, commercialization, and technological advancements. These batteries have transformed various industries, enabling the proliferation of moveable electronics, facilitating the implementation of electric vehicles, and supporting the incorporation of renewable energy foundations into the authority network.

Types of Lithium-Ion Batteries

Lithium-ion batteries are classified as:

Lithium carbonate

The preparation of lithium carbonate involved purifying the lithium-rich leach solution (PLS) by adjusting the pH and filtering out impurities. The resulting clear filtrate was then reacted with sodium carbonate under controlled conditions to produce lithium carbonate. Different concentrations of lithium were examined by diluting and evaporating the clear filtrate. The lithium carbonate products underwent washing and drying processes to remove residual water. The purity and impurity content were analyzed using acid-base titration, atomic absorption spectroscopy (AAS), and inductively coupled plasma optical emission spectroscopy (ICP-OES). The particle size distribution of the lithium carbonate was determined using a Malvern Mastersizer 3000 instrument (Peng et al., 2019). Lithium-ion batteries using $LiCoO_2$ as the positive electrode (cathode) material offer extraordinary energy thickness, making them appropriate for submissions such as portable electronics. LCO batteries have good cycling stability but may exhibit safety concerns and limited thermal stability (Gao et al., 2017).

Lithium hydroxide

Lithium hydroxide (LiOH) is a compound used in the manufacture of lithium-ion batteries, particularly for cathode materials. It serves as a precursor for the synthesis of various lithium compounds, including lithium nickel cobalt aluminum oxide (NCA), lithium iron phosphate (LFP), and lithium manganese oxide (LMO), among others (Lain, 2001). The preparation of lithium hydroxide typically involves the reaction of lithium carbonate (Li_2CO_3) with water (H_2O) or the treatment of lithium oxide (Li_2O) with water. The resulting lithium hydroxide can then be used as a starting material for the synthesis of cathode materials in lithium-ion batteries (Liu & Azimi, 2022).

In the battery manufacturing process, lithium hydroxide is combined with other elements, such as cobalt, nickel, manganese, or iron, to form the cathode materials. These cathode materials show a critical character in the inclusive presentation of lithium-ion batteries, determining influences such as energy density, cycle life, and thermal stability (Sonoc et al., 2015). Lithium hydroxide offers advantages for battery applications due to its high lithium content, which contributes to higher energy storage capacity. Additionally, it exhibits good solubility in water and can be easily processed into various forms suitable for battery electrode manufacturing (Horstmann et al., 2013). Overall, lithium hydroxide plays a vital role in the production of cathode materials for lithium-ion batteries, contributing to the expansion of high-performance energy-packing organizations used in moveable electronics, electric vehicles, and grid-scale energy loading submissions.

Lithium metal

Lithium metal-based lithium-ion batteries, also known as lithium-metal batteries, utilize metallic lithium as the anode material, contributing higher energy thickness and potential for greater capacity compared to graphite-based anodes (Liu et al., 2018). These batteries operate by plating and stripping lithium ions on the lithium metal anode during the charging and discharging processes. However, the formation of lithium dendrites poses safety concerns, which can cause internal short circuits and compromise battery stability. Research focuses on developing advanced electrolytes and protective coatings, including solid-state electrolytes, to mitigate dendrite formation and improve safety (Li et al., 2021). Lithium-metal batteries hold promise for enhancing energy density and performance but require further advancements to ensure safety and stability before widespread commercialization (Wang & Cao, 2008).

Butyl lithium

Butyl lithium is an organolithium compound that contains lithium and butyl groups. It is commonly used as a strong base and as a reagent in organic synthesis. Butyl lithium is highly reactive and typically exists as a solution in nonpolar solvents, such as hexanes or cyclohexane. It is used in various chemical reactions, such as deprotonation reactions, and metalation reactions, and as a catalyst in polymerization processes (Noailles et al., 1999).

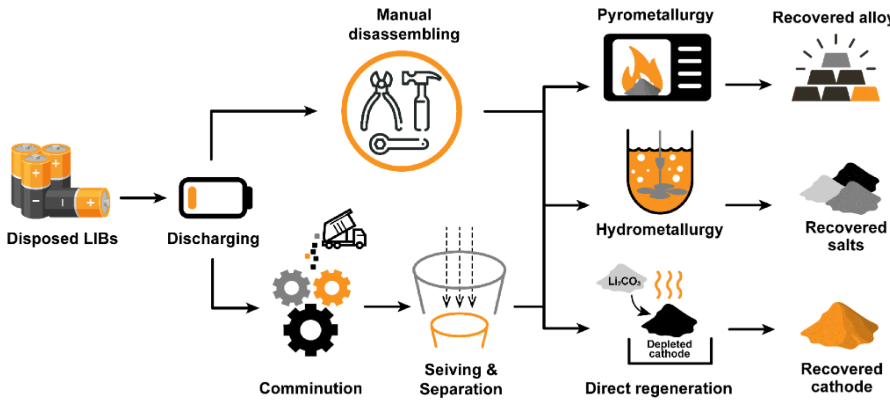


Figure 3:Recycling process of Lithium specialty batteries Ref. (Akhmetov et al., 2023). ©2023 by the authors

Lithium specialties

Lithium specialty batteries refer to a class of batteries that utilize lithium as the active material in their electrodes. These batteries offer high energy thickness, ongoing presentation, and lightweight characteristics. They are frequently cast-off in submissions where small size, high energy capacity, and durability are crucial, such as in moveable microchip technology, medical devices, electric automobiles, and renewable energy-storing schemes. Lithium-ion (Li-ion) batteries and lithium polymer (LiPo) batteries are two common categories of lithium specialty batteries recycled in various devices and industries, as shown in Figure 3 (Park et al., 2020).

Table 1
Literature of Lithium-Ion batteries by different scientists

Study	Authors	Ref. Year	Methodology	Findings
A Comprehensive Review of Recycling Technologies for Lithium-Ion Batteries	Jin, S. et al.	2022	Review paper	Provides an overview of various recycling technologies for lithium-ion batteries, including mechanical, hydrometallurgical, and pyrometallurgical processes. Discusses the challenges and opportunities associated with battery recycling.
An overview on the recovery of cobalt from end-of-life lithium-ion batteries	Mansur, M.B, et al.	2022	Review paper	Discusses the hydrometallurgical approaches for recovering lithium and cobalt after consumed lithium-ion batteries. Evaluates the efficiency and environmental impacts of different recovery methods.
Life Cycle Assessment of Recycling Lithium-Ion Batteries: A Review	Arshad et al.	2022	Review paper	Conducts a life cycle assessment (LCA) of recycling lithium-ion batteries, evaluating the environmental impacts associated with different recycling processes. Provides insights into the sustainability of battery recycling.
The valorization of resources from end-of-life lithium-ion batteries: A review	Duarte Castro et al.	2022	Review paper	Explores the pyrometallurgical processes for the valorization of consumed lithium-ion batteries. Highlights the rescue of valuable metals such as lithium, cobalt, and nickel through thermal treatment techniques.

Study	Authors	Ref. Year	Methodology	Findings
Comprehensive evaluation on production and recycling of lithium-ion batteries: A critical review	Ren, et al.	2023	Critical Review	Compares the environmental and economic aspects of different lithium-ion battery recycling methods, including mechanical, hydrometallurgical, and pyrometallurgical processes. Assesses their sustainability and feasibility.

Properties

Properties of lithium-ion batteries include high energy thickness, lightweight design, rechargeability, little self-discharge proportion, versatility in applications, and the potential for different chemistries and configurations (Maleki et al., 1999). The performance of lithium-ion batteries under conditions of low high temperature or rapid charge/discharge rates is influenced by the inherent movement of electrolytes and the thermodynamic characteristics of frequently employed binary electrolyte solutions, as shown in tables 2,3. In advancing upcoming electrolyte options, it is crucial to quantify ionic conductivity, binary diffusion coefficient, transference number, and thermodynamic factor across a wide spectrum of concentrations and temperatures (Landesfeind & Gasteiger, 2019).

Thermal Properties

The thermal properties of lithium-ion batteries are essential to their safe and efficient operation (Ravdel et al., 2003). Some key thermal properties include: This mentions to the capability of the battery's materials to conduct heat. High thermal conductivity helps in distributing and dissipating heat generated during operation, reducing the risk of overheating (Sanker & Baby, 2022). This property indicates how much heat energy a battery material can absorb or release while its temperature changes. It plays a part in defining how the battery's temperature changes during charging, discharging, and other operations (Al-Zareer et al., 2021). As the battery heats up during operation, its components can expand. Understanding thermal expansion is crucial to preventing mechanical stress or damage within the battery (Sanker & Baby, 2022).

This is the temperature at which the battery's internal reactions become self-sustaining, leading to rapid heating and potential catastrophic failure. Battery designs aim to prevent thermal runaway or control it if it occurs (Liu et al., 2018). The battery generates heat due to resistive losses and chemical reactions during charge and discharge. Proper cooling mechanisms or heat dissipation strategies are crucial to keeping the battery's temperature inside harmless bounds (Duan et al., 2021). Effective thermal management systems, such as cooling fins, heat sinks, and phase-change materials, are used to regulate the battery's temperature and prevent overheating (Zichen & Changqing, 2021). Lithium-ion batteries have optimal temperature ranges for performance and safety. Operating outside these ranges can lead to reduced capacity, accelerated degradation, or safety risks (Tron et al., 2019). Battery materials should be thermally stable to avoid unintended reactions or decomposition at high temperatures (Chen et al., 2020). How quickly a battery can respond to temperature changes is important for maintaining stability during rapid charge and discharge cycles (Li et al., 2019).

Mechanical Properties

The mechanical properties of lithium-ion batteries are important for their structural integrity, safety, and overall performance (Kermani & Sahraei, 2017). Some key mechanical properties include: Battery components, such as the casing, electrodes, and separators, need to have sufficient strength and rigidity to withstand external forces and prevent deformation or damage during handling, assembly, and operation (Ladpli et al., 2019). In some applications, batteries may need to be flexible to conform to curved surfaces or fit into unique spaces. Flexible batteries should maintain their integrity without compromising safety or performance (Cha et al., 2018). Battery materials should exhibit elastic behavior to absorb and recover from small deformations caused by thermal expansion, mechanical stress, or impact. Excessive deformation can lead to short circuits or other safety risks (Diener et al., 2022). As batteries go through charge and discharge cycles, they may experience mechanical stress due to volume changes in the electrodes. A battery's mechanical properties should allow it to withstand these repeated expansions and contractions without degradation (Liu et al., 2018). Batteries can be subject to impact during transportation, installation, or use. Having good impact resistance helps prevent physical damage and maintains the battery's functionality (Ma et al., 2018). Batteries in numerous submissions, such as automobiles or moveable devices, might experience vibrations. Proper mechanical properties help batteries endure these vibrations without structural failure (Zhang et al., 2017).

Table 2

Properties, Advantages, and Disadvantages of Different Types of Lithium-Ion Batteries

Types of Li^+ ion batteries	Advantages	Disadvantages	Properties	Ref.
Lithium carbonate	LCO offers high energy thickness and manufacture them appropriate for submissions such as portable electronics. LCO batteries have good cycling stability but may exhibit safety concerns and limited thermal stability	have a limited energy density compared to some alternative technologies like hydrogen fuel cells. Extracting the materials for these batteries can be environmentally destructive, and recycling them can be challenging.	High Energy Density Rechargeability Wide Operating Temperature Range High Voltage Fast Charging Low Maintenance	Zhao et al., 2018
Lithium hydroxide	Lithium hydroxide-based electrolytes tend to be more thermally stable than some other lithium-ion battery electrolytes, such as lithium carbonate. Lithium hydroxide batteries can activate effectively in a wide-ranging temperature choice, making them appropriate for use in both extremely cold as well as hot environments.	Lithium hydroxide batteries have a finite lifespan, characterized by a certain number of charge and discharge cycles. can be chemically unstable, especially when damaged.	Reduced Thermal Sensitivity Fast Charging Reduced Thermal Sensitivity Reduced Risk of Dendrite Formation Long Cycle Life	Liu et al., 2021
Lithium metal	They are often more durable and robust than some other battery types, making them suitable for applications that require resilience to physical stress and environmental conditions. Lithium-metal batteries are frothy, so manufacture them well-suited for moveable and wearable campaigns	Lithium-metal batteries can be relatively expensive compared to other non-rechargeable battery types. Due to their non-rechargeable nature and safety concerns, lithium-metal batteries are primarily cast-off in niche applications, such as medical devices, pacemakers, remote sensors, and some	Instant Activation Low Maintenance High Discharge Current Compact Design	Wang et al., 2021

Types of Li^+ ion batteries	Advantages	Disadvantages	Properties	Ref.
	where heaviness is a dangerous feature.	military equipment.		
Butyl lithium	These are more environmentally outgoing than some other battery chemistries because they do not contain poisonous heavy metals like lead-acid batteries. These batteries offer a high energy thickness, which means they can store a large quantity of energy for their size and weight.	Due to protection alarms related to the danger of thermal escape, batteries may be subject to transportation regulations and restrictions, adding complexity to their shipping and handling.	High Voltage Rechargeability Wide Operating Temperature Range	Xu et al., 2006
Lithium specialties	These batteries offer high energy density, long-lasting performance, and lightweight characteristics. They are usually cast-off in applications where small size, high energy capacity, and durability are crucial, such as in moveable electronics, medical devices, electric vehicles, and renewable energy storing systems.	have significant limitations, including being non-rechargeable, safety concerns related to thermal runaway, and limited lifespan.	Instant Activation Low Maintenance High Discharge Current	Nazri & Pistoia, 2008

Energy storage in Li-ion batteries

Our society's most demanding anxieties are the period after fossil fuels to renewable dynamism bases such as breeze and lunar authority. Well-organized authority loading is needed for this changeover to switch impulsiveness in renewable sources and calm down electrical linkages. To accomplish electrical flexibility, amalgam and electronic automobile submissions necessitate well-organized influence packing (Wagemaker & Mulder, 2013).

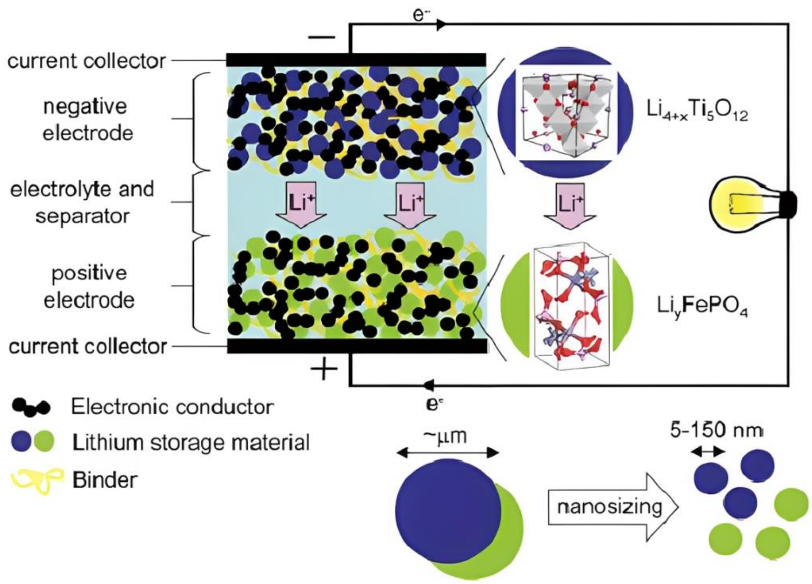


Figure 4. Schematic principle of a Li-ion battery Ref. (Wagemaker & Mulder, 2013). ©2012 American Chemical Society

Electrochemical storage is appealing due to its high storage efficiencies, usually above 90%, and the use of Nanosized Supplement Materials in Li-Ion Batteries by Wagemaker and Mulder results in comparatively high energy thicknesses (Kumar et al., 2019). The use of Li-ion batteries in amalgam and electric automobiles, as well as in stationary storage, is becoming more common, but enhancements in performance, cost efficiency, and safety are necessary. This has sparked global investigations for Li-ion electrode materials that possess desired characteristics like high energy and power density, affordability, abundant elements, and chemical stability (Ellis et al., 2010). The most crucial type of electrodes in present-day Li-ion batteries are the supplement materials that can host lithium reversibly within their crystal structure. While the outlook for Li-ion batteries appears optimistic, it is important to highlight that the supply of various essential transition metals, including lithium, is an area of concern (Wagemaker & Mulder, 2013). Even though the outlook for Li-ion batteries seems promising, it is important to consider the supply of various transition metals and potentially lithium itself. In a Li-ion battery, two electrodes made of insertion materials have different lithium chemical potentials and are connected by an electrolyte that acts as an ionic conductor and electronic insulator, as shown in Figure 4. The lithium will move from the material it is inserted in with a high chemical potential of Li towards the electrode with a lower chemical potential of Li. Only lithium ions can move through the electrolyte, requiring electrons to travel alongside them in the external circuit to power a device. Applying a higher electrical potential than the unprompted equilibrium open circuit divergence can reverse the development. A high level of energy density necessitates a significant ion-specific capacity in both electrodes and a considerable disparity in chemical potential. Significant supremacy necessitates strong mobility of both electrons and Li ions within the electrode materials and electrolyte (Deng, 2015).

The conductor material is normally understood to confine the charge transportation in the battery-operated, together with both ionic and electrical passageways. Frequently recycled resources aimed at supplementing are transition metal oxides and phosphates, which have little electronic and ionic conductivity. The latest trainings have focused on manufacturing electrode constituents slightly at the nanoscale. This has the possibility to increase (dis)charge amounts by limiting the dispersion alleyway for Li-ions and electrons inside the substantial. The inadequacy of the extensive superficial zone of nanostructured constituents is the inferior steadiness of nanomaterials leading to electrode dissolution and multifaceted reactivity towards electrolytes at voltages minor than 1 V equated to Li/Li+, potentially impacting the performance of Li-ion batteries. A thinkable shortcoming is the condensed volumetric vitality concentrations due to the less condensed stuffing. Transition metal oxides and phosphates that are moderately steady can take improvement of nanosizing, accomplishment successfully in the electrolyte's constancy series (Zhang & Ran, 2021).

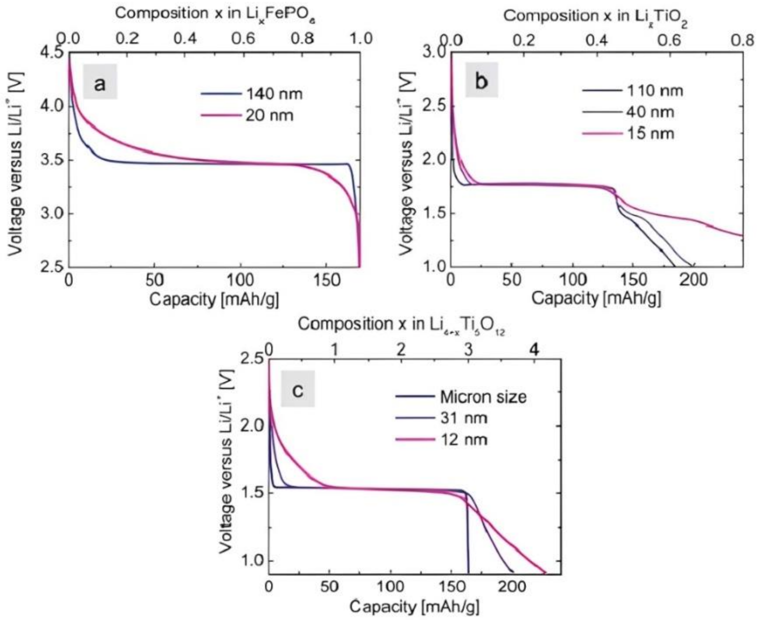


Figure 5. Voltage profiles of different particle sizes Ref. (Wagemaker & Mulder, 2013). ©2012 American Chemical Society

Numerous current conclusions display that dipping the extent of electrode subdivisions to the nanoscale ominously disturbs physical belongings, awarding mutual opportunities and experiments for better-quality Li-ion storage. These clarifications contain the dispersion of the energy outline, modifications in solubility bounds and segment performance, unforeseen kinetics, and increased measurements, as shown in Figure 5. The foremost investigation is whether the fluctuations are uniquely an outcome of enlarged surface area and dumpier diffusion distances, or if nanosizing also disturbs significant constituent's belongings like defect chemistry and thermodynamics in a substantial method. The applied examination associated with the main topic in what way the reformed nanomaterial belongings can increase battery performance (Hasan et al., 2020).

Up-to-date education on nanoscale supplement resources in Li-ion sequences have provided a larger consideration of the special effects of nanosizing. Nonetheless, removing a unified image endures to pose encounters. This explanation pursues to gather present explanations on critical electrode resources to advance a unified understanding of nanoscale influences on insertion constituents and their competence to advance battery performance. The resources declared are olivine $LiFePO_4$ (positive electrode), anatase/rutile/brookite/bronze TiO_2, and spinel $Li_4Ti_5O_{12}$ (negative electrodes). The size-related occurrences that have been discoursed appear to be a common manifestation in two-phase intercalation organizations, as shown by the consequences of scholarships on LixTiO2 and MgHx systems. Initially, we will survey the nanoscale impressions of each electrode material unconnectedly, and then we will amalgamate our conclusions and discover how these nano belongings can improve the presentation of Li-ion batteries (Li-ion) (Jung et al., 2019).

Table 3
Comparison of Primary and secondary Lithium-ion batteries

Characteristics	Primary Batteries	Secondary Batteries	Ref
Rechargeability	Primary lithium-ion batteries are non-rechargeable. Once they are depleted, they cannot be recharged and must be disposed of properly.	Secondary lithium-ion batteries are rechargeable. They can be charged and discharged numerous periods, allowing for reuse over an extended period.	Hayner et al., 2012
Lifespan	Primary lithium-ion batteries have a limited life cycle and	Secondary lithium-ion batteries have a lengthier lifespan and	Lai et al., 2022

Characteristics	Primary Batteries	Secondary Batteries	Ref
	are designed for a single use. They are typically optimized for long shelf life and high initial capacity.	can endure hundreds to thousands of charge and discharge cycles earlier undergoing noteworthy capability squalor.	
Energy Density	Primary lithium-ion batteries often have an advanced initial energy thickness compared to secondary batteries of the same size and weight.	secondary lithium-ion batteries may have slightly lower initial energy density, but they can provide more total energy over their lifetime due to reusability.	Choi & Aurbach, 2016
Environmental Impact	Primary lithium-ion batteries are deliberated more environmentally friendly for certain applications due to their lengthier shelf life and lower self-discharge rate, reducing waste.	Secondary lithium-ion batteries are less environmentally responsive for disposable applications due to their limited lifespan and the eventual need for recycling.	Gaines & Dunn, 2014
Initial Cost	Primary lithium-ion batteries are typically less expensive upfront, which can be advantageous for devices with low power requirements and a short lifespan.	Secondary lithium-ion batteries may have a developed initial cost but are better worth over time due to their rechargeability.	Diouf & Pode, 2015
Safety Considerations	Primary lithium-ion batteries are generally considered safer because they do not undergo the repetitive charge and discharge cycles that can prime to security concerns in secondary batteries.	Secondary lithium-ion batteries have more complex safety requirements and are more prone to thermal runaway or safety issues if mistreated or damaged.	Wen et al., 2012
Applications	Primary lithium-ion batteries are usually used in campaigns where long shelf life, low self-discharge, and a single-use requirement are essential, such as medical devices, smoke detectors, and some military equipment.	Secondary lithium-ion batteries are used in an extensive variety of applications, including consumer electronics (e.g., smartphones, laptops), electric automobiles, energy storage schemes, and more, where rechargeability and long-term use are critical.	Pistoia, 2013

Model Development

This learning utilized a 10 Ah (Qt) lithium-ion battery from Changsha Ye Xiang New Energy Co., Ltd., which involved a $LiFePO_4$ cathode, graphite anode, and porous separators occupied through plasticized electrolyte. The battery remained accumulated by continually layering in the described sequence: separator + anode (both sides) + separator + cathode (both sides) + separator + anode (both sides) +…+ cathode (both sides) + separator + anode (both sides) + separator. In Figure 6 (a), the battery's structure is depicted. Due to the presence of the internal repeating component, a cell element involving five parallel battery elements, as shown in Figure 6 (b), was chosen to streamline the calculation process. In Figure 6 (b), it is illustrated that the electrode tabs assist as the existing gatherers that protrude from the four-sided absorbent electrodes, and they are not glazed with energetic resources. Certainly, the cathode tabs and anode tabs are joined and collected distinctly. In this example, we undertake that both the cathode tabs and anode tabs are not associated, and the inclusive current is equally circulated among each tab. 66 single cells are arranged to produce the complete device's battery, which generates a thickness of approximately 10 mm in the x direction. Hence, the full current transient through one cell (I total) can be considered in the following manner: (3D) (Li et al., 2015)

$$I_{total} = NQ_t / N_t - 1$$

How Much Recyclable/ Rate of Recycling

The current lithium-ion battery reprocessing amount is roughly 5-10%, and this proportion may fluctuate due to influences such as locality, rules, and technological development, as there are incessant happenings to boost reprocessing approaches and techniques for mining appreciated ingredients from old batteries, as shown in Table 4 (Huang et al., 2018).

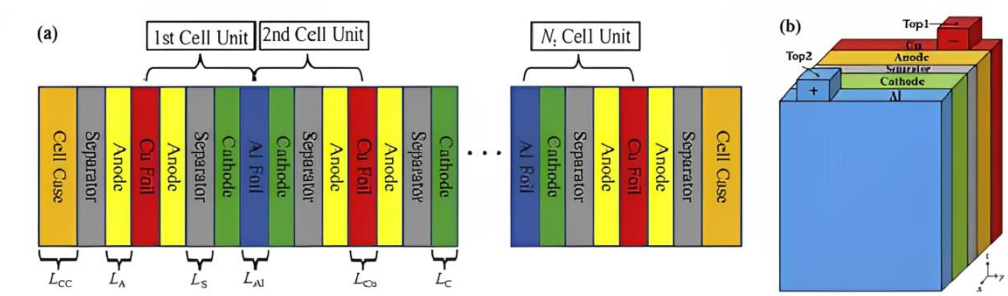


Figure 6:(a) Schematic diagram of lithium-ion battery with a planar tabbed configuration and (b) computational domain Ref. (Li et al., 2015). © 2015 Elsevier B.V.

Common methods used for recycling lithium-ion batteries

Mechanical Shredding
Mechanical shredding is commonly used for reprocessing lithium-ion batteries since it can competently and cost-effectively break down batteries. It is crucial to acknowledge that the technique may lead to the discarding of appreciated resources. Other recycling methods, such as hydrometallurgical or pyrometallurgical processes, may be used in combination with mechanical shredding to maximize material recovery (Chakraborty & Saha, 2022).

Sieving and Sorting
Sieving and sorting are approaches of parting engaged in reprocessing lithium-ion batteries to extract appreciated ingredients from ragged battery fragments. Mutual screening and establishing are essential mechanisms of the reprocessing development for lithium-ion batteries, as they assist with the operative separation and repossession of appreciated constituents. They are commonly operated together with other reprocessing procedures to enhance the repossession of constituents for recycling or suitable clearance (Latini et al., 2022).

Pyrometallurgical Process
The pyrometallurgical technique is engaged in the reprocessing of lithium-ion batteries, where high temperatures are employed to extract valuable metals from battery fragments. Pyrometallurgical recycling professionally regains appreciated metals from lithium-ion batteries and minimizes waste. However, it has some challenges, such as the potential for emissions and the need for careful management of hazardous materials. Consequently, ecological guidelines and appropriate production switches are crucial to guarantee the sustainability and security of the development (Rajaeifar et al., 2021).

Hydrometallurgical Process
The hydrometallurgical process is a recycling method used for lithium-ion batteries that involves chemical solutions to extract valuable metals from battery components. Hydrometallurgical recycling offers advantages like selective metal recovery and reduced emissions compared to high-temperature processes. However, it requires careful management of chemicals, effluents, and residues to ensure environmental sustainability. Regulations and proper handling of hazardous materials are crucial components of successful hydrometallurgical recycling processes (Jiang et al., 2022).

Direct Recovery

"Direct Recovery" is a phrase frequently used to mention a reprocessing technique where appreciated ingredients are directly improved from old lithium-ion batteries. The importance is on removing specific metals or materials right from the batteries deprived of the requirement for widespread preprocessing. Direct recovery methods are still being enhanced and strengthened for specific battery types or materials. Their goal is to increase the effectiveness and sustainability of battery recycling by streamlining the procedure and removing appreciated resources straight from castoff batteries (Ji et al., 2023).

Thermal Treatment

Thermal treatment is a recycling method used for lithium-ion batteries that involves subjecting battery components to high temperatures to facilitate the recovery of valuable materials and minimize waste. Thermal treatment offers advantages in terms of material recovery and waste reduction. However, it requires careful management of emissions, residues, and energy consumption to ensure environmental sustainability and safety (Kim et al., 2021).

Electrochemical process

Electrochemical processes are a recycling method used for lithium-ion batteries that involves using electrochemical reactions to recover valuable materials from battery components. Electrochemical recycling methods offer advantages in terms of selective metal recovery and energy efficiency. However, they require precise control of electrochemical reactions, careful management of chemicals, and proper disposal of residues to ensure the sustainability and safety of the process (Li et al., 2023).

Table 4
Features of Lithium-ion Batteries

Features	Effects on Lithium-Ion Batteries	Ref.
Efficiency	The competence of lithium-ion batteries, which depends on factors like chemistry, temperature, and cycling, typically ranges from 90% to 95%, affecting their ability to convert and store energy effectively.	Rodrigues et al., 2017
Toxicity	Lithium-ion batteries can pose ecological and social fitness risks owing to the venomousness of their mechanisms, including lithium, cobalt, nickel, and other materials, especially when not properly managed during production, use, and disposal.	Nedjalkov et al., 2016
Environmental Impact	Lithium-ion batteries present environmental concerns throughout their life cycle, including resource extraction, manufacturing, use, and disposal, necessitating efforts to mitigate their impact.	Mrozik et al., 2021
Reliable	The dependability of lithium-ion batteries varies, founded on factors like quality of manufacturing, operating conditions, maintenance, and proper usage, with concerns including capacity degradation, safety risks, and performance inconsistencies.	Rahman & Alharbi, 2024

Application

Why these Lithium-ion batteries are environmentally friendly?

Lithium-ion batteries have developed progressively collectively because of their numerous benefits, such as being ecologically friendly (Rana et al., 2023). They are considered more sustainable than other battery technologies for several reasons. Their high energy efficiency is one factor. Lithium-ion batteries outclass supplementary batteries in expressions of energy thickness, allowing them to grasp additional energy in a compressed and insubstantial project.

This advanced vitality thickness empowers vigor loading to previous extensive and is more well-organized, thus decreasing the inclusive environmental footprint of battery manufacturing and disposal (Kuznetsov et al., 2023). Lithium-ion batteries are also highly recyclable, which contributes to their environmental sustainability (Du et al., 2022). The recycling process involves recovering appreciated resources alike lithium, cobalt, nickel, and copper that can be recycled in original batteries (Ordoñez et al., 2016). Recycling these materials decreases the demand for mining and extracting new resources, minimizing environmental impacts associated with resource extraction (Pell et al., 2021).

In terms of greenhouse gas releases, the manufacture of lithium-ion batteries emits fewer gases compared to other battery technologies (Liang et al., 2017). This is due in part to the fact that lithium-ion batteries require fewer raw materials and have a more efficient manufacturing process (Philippot et al., 2019). As a result, the carbon footprint associated with lithium-ion battery production is relatively low (McManus, 2012). Lithium-ion batteries also facilitate the incorporation of renewable vitality bases hooked on the electrical grid by stowing additional dynamism produced throughout top manufacture stages and discharging it throughout periods of high demand (Chen et al., 2020). Energy storage competence soothes the network and decreases dependence on fossil fuel authority plants, thus decreasing greenhouse gas releases (Tan et al., 2021).

Lithium-ion batteries also have a lengthier lifetime than other battery machinery, with an advanced cycle life (Lai et al., 2022). This prolonged life cycle diminishes the occurrence of battery substitutions, consequential in less leftover and lower ecological impression (Haram et al., 2021). The custom lithium-ion series in electric vehicles produces zero tailpipe emissions, reducing air pollution and improving air quality (Tran et al., 2020). If thrilling using renewable energy, electric vehicles motorized by lithium-ion batteries can reduce overall greenhouse gas emissions (Hao et al., 2017). However, challenges remain regarding the manufacture and removal of lithium-ion batteries. The withdrawal of rare resources like lithium and cobalt can have destructive environmental and social impacts if not managed responsibly (Murdock et al., 2021). Additionally, lithium-ion battery recycling infrastructure is still developing in many regions, leading to batteries ending up in landfills (Winslow et al., 2018). In summary, lithium-ion batteries are considered environmentally friendly owing to their great energy efficiency, recyclability, reduced greenhouse gas emissions, potential for renewable energy integration, and longer lifespan (Diouf & Pode, 2015). However, improving the sustainability of their entire lifecycle remains an important goal to maximize their environmental benefits.

Conclusion

The market for lithium-ion batteries is expanding quickly as a result of the popularity of electric vehicles. Still, the processes used in manufacturing and recycling have a big effect on the environment. To develop a circular economy for the lithium-ion battery sector, new sustainable recycling methods must be used as the rate at which new batteries are manufactured exceeds the rate at which they are now recycled. The predominant recycling technique used today is pyrometallurgy, which uses a lot of energy and releases harmful flue gases. With encouraging lab-scale research, hydrometallurgy techniques provide a competitive alternative and point the way toward industrial-scale recycling methods that can rival lithium-ion battery manufacturing. These approaches not only reclaim valuable resources such as lithium, cobalt, and nickel but also foster a circular economy. Nonetheless, obstacles persist in enhancing efficiency, minimizing expenses, and amplifying processes. With the increasing demand for batteries, effective recycling procedures will be essential in reducing environmental impact and securing resource availability. Future innovations must emphasize environmentally sustainable and economically feasible solutions to attain global sustainability objectives.

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