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A comprehensive review of advances in Lithium-ion batteries: Materials, challenges, applications, and future prospects

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ABSTRACT
Lithium-ion batteries have created as the establishment of cutting edge essentialness capacity, fueling electric vehicles, renewable essentialness systems, and flexible contraptions. In show disdain toward of their tall essentialness thickness and cycle life, challenges in execution, security, gotten, and viability hold on. This study synthesizes afterward headways in anode materials, checking cathodes, anodes, and electrolytes, with a center on inorganic chemistry and informative strategies such as X-ray diffraction (XRD), sifting electron microscopy (SEM), and electrochemical impedance spectroscopy (EIS). Specialized challenges, such as confined capacity and fire perils, money related boundaries like rough texture costs, and characteristic issues, tallying inefficient reusing, are essentially analyzed. Applications in electric vehicles, renewable imperativeness capacity, and flexible contraptions are explored, with emphasis on Vietnam's setting, exemplified by VinFast's electric vehicle era and renewable imperativeness advancement. Future prospects join cobalt-free materials, solid-state electrolytes, and advanced reusing. This study highlights Vietnam's potential to improvement family battery ask around, supporting its green imperativeness strategy and viable enhancement.

Keywords: Lithium-ion batteries, electrode materials, inorganic chemistry, electric vehicles, renewable energy, Vietnam.

I. INTRODUCTION

Lithium-ion batteries have changed imperativeness capacity, getting to be imperative in electric vehicles, flexible equipment, and renewable imperativeness systems. Their tall essentialness thickness, expanding from 150 to 250 Wh/kg, and near-100% coulombic adequacy make them culminate for get together the increasing demands of display day society (Blomgren, 2016). In any case, hindrances in execution, security, taken a toll, and normal influence pose essential hindrances to their prudent change, requiring ceaseless ask almost and advancement (Goodenough & Kim, 2010). These challenges are particularly critical in creating economies like Vietnam, where the rise of electric vehicle businesses and renewable imperativeness wanders underscores the require for advanced battery progresses (Sharma et al., 2025).

The enhancement of lithium-ion batteries takes after back to early 20th-century considers almost on lithium cathodes, with essential focuses of reference inside the 1970s when Whittingham (2004) displayed inorganic cathode materials like LiCoO2 (Lewis & Keyes, 1913). Resulting headways by Goodenough (2013) made strides cathode robustness with materials such as LiFePO4, clearing the way for commercialization by Sony in 1991, as popular by Scrosati (2011). This breakthrough checked the primary light of versatile contraptions, on a really fundamental level changing development scenes. These days, the around the world pushed for electric vehicles and renewable imperativeness has increases ask around into novel materials, checking cobalt-free cathodes and silicon anodes, to progress execution and diminish costs (Manthiram, 2011; Gopinadh et al., 2024).

In show disdain toward of these advances, lithium-ion batteries go up against essential impediments. Security perils, such as warm runaway driving to fires, remain a concern, particularly in high-temperature or mechanically compromised conditions (Mauger & Julien, 2017). The tall taken a toll of unrefined materials, tallying lithium and cobalt, and complex creating shapes control sensibility, especially in making nations (Boretti, 2023). Normal challenges are so also crushing, with mining works out causing water and soil defilement and reusing rates reflecting underneath 5% in various locale (Ould Ely et al., 2019). In Vietnam, the speedy advancement of

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electric vehicle era, driven by VinFast, and renewable essentialness exercises, such as sun fueled and wind control, highlight the criticalness of making private battery innovations to decrease reliance on imported materials (Sharma et al., 2025).

From an inorganic chemistry perspective, descriptive strategies play a critical portion in advancing battery ask around. Techniques such as X-ray diffraction (XRD) clarify cathode gem structures, though sifting and transmission electron microscopy (SEM/TEM) reveal anode nanoscale morphologies. Electrochemical impedance spectroscopy (EIS) gives bits of knowledge into interface resistance, empowering optimization of battery plan (Nitta et al., 2015). These instruments are fundamental for creating materials that upgrade execution and supportability.

This study focuses to supply a comprehensive amalgamation of afterward development in lithium-ion battery development, with a center on inorganic materials, checking cathodes, anodes, and electrolytes. It essentially analyzes specialized, monetary, and common challenges, explores commonsense applications, and highlights Vietnam's portion inside the around the world battery scene, particularly through VinFast's electric vehicle era and renewable imperativeness improvement. The review as well proposes future headings to form strides battery execution and maintainability, emphasizing the potential for teach similar to Thai Nguyen University of Technlogy (TNUT) to lead family ask almost endeavors. By joining encounters from inorganic chemistry and informative strategies, this work offers a vital resource for investigators, engineers, and policymakers, contributing to the around the world intrigued of prudent essentialness courses of action and supporting Vietnam's green essentialness method.

Materials in Lithium-ion batteries

The execution of lithium-ion batteries turns on the properties of their cathode materials, with cathodes playing a fundamental portion in choosing capacity and robustness. Early work by Whittingham (2004) set up $LiCoO_2$ as a benchmark cathode texture, publicizing tall essentialness thickness but persevering from tall costs due to cobalt and warm instability threats. Ensuing headways displayed $LiNiMnCoO_2$ (NMC) and $LiFePO_4$ (LFP), which alter capacity, security, and sensibility (Manthiram, 2011). NMC cathodes allow higher capacity, while LFP is favored for its moo brought and sturdiness, making it a favored choice for electric vehicles. Afterward ask almost has moved toward cobalt-free cathodes, such as manganese- or nickel-rich materials, to relieve natural and monetary concerns. For event, NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) finishes capacities outperforming 200 mAh/g, in show disdain toward of the reality that challenges in warm dauntlessness hold on (Xu et al., 2023). Illustrative strategies like X-ray diffraction (XRD) are instrumental in characterizing cathode valuable stone structures, though X-ray photoelectron spectroscopy (XPS) reveals oxidation states, supporting in execution optimization (Sharma et al., 2025). These headways emphasize the centrality of inorganic chemistry in making viable cathode materials.

Anodes are so also pivotal, with graphite serving as the standard due to its dauntlessness, in show disdain toward of a confined theoretical capacity of 372 mAh/g (Goodenough & Kim, 2010). To overcome this restriction, investigators have explored silicon, which offers anastounding capacity of generally 4200 mAh/g but perseveres from critical volume advancement (>300%) in the midst of cycling, driving to texture part (Gopinadh et al., 2024). Silicon-carbon composites and nanostructured materials have risen as courses of action to update robustness, while lithium metal anodes, with a capacity of 3860 mAh/g, ensure undoubtedly more unmistakable potential.

In any case, lithium metal faces challenges from dendrite course of action and insecure solid electrolyte interphase (SEI) layers. Illustrative gadgets such as checking electron microscopy (SEM) and transmission electron microscopy (TEM) donate nitty coarse encounters into nanoscale anode morphologies, while electrochemical impedance spectroscopy (EIS) surveys interface resistance, coordinating endeavors to calm capacity obscure (Sharma et al., 2025). These progressions highlight the require for inorganic texture advancements to open higher anode execution.

Electrolytes and separators are fundamental for ensuring molecule transport and security in lithium-ion batteries. Standard liquid electrolytes, routinely based on lithium salts like $LiPF_6$, offer tall ionic conductivity but pose fire threats due to their combustibility (Nitta et al., 2015). Solid-state electrolytes, tallying oxides, sulfides, and polymers, are being inspected to overhaul security and imperativeness thickness, in show disdain toward of the truth that moo ionic conductivity at room temperature remains a obstacle (Xu et al., 2023). Separators, routinely

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made from polymers or ceramics, move forward warm consistent quality but require predominant compatibility with terminals to play down resistance (Sharma et al., 2025). Informative methods such as Fourier-transform infrared spectroscopy (FTIR) and nuclear alluring resonation (NMR) are utilized to characterize electrolyte structures, giving data to optimize molecule transport. From an inorganic chemistry perspective, the advancement of oxide- or sulfide-based solid electrolytes talks to a promising street to advance battery security and execution, tending to key controls in current propels.

Challenges of Lithium-ion batteries

The specialized challenges of lithium-ion batteries center on anode execution, security, and cycle life. Cathodes like LiCoO2 offer limited capacities (~140 mAh/g), while silicon anodes, in show disdain toward of tall theoretical capacities, degenerate rapidly due to volume advancement in the midst of cycling (Goodenough & Kim, 2010). Liquid electrolytes, though conductive, are combustible, extending the danger of warm runaway and fires, particularly underneath tall temperatures or mechanical hurt (Mauger & Julien, 2017). Solid-state electrolytes ensure made strides security but persevere from tall interfacial resistance, obliging their down to soil determination (Xu et al., 2023). Informative strategies such as electrochemical impedance spectroscopy (EIS) and X-ray diffraction (XRD) are fundamental for understanding corruption rebellious, in any case making unfaltering materials remains a complex task (Sharma et al., 2025). Cycle life is another concern, as the course of action of solid electrolyte interphase (SEI) layers and texture breaking reduce capacity over hundreds of cycles, requiring improvements in texture arrange (Nitta et al., 2015).

Budgetary challenges development complicated the remote coming to apportionment of lithium-ion batteries. The tall taken a toll of rough materials, particularly lithium, cobalt, and nickel, drives up era costs, with cobalt-based cathodes being especially over the top (Manthiram, 2011). Creating shapes are complex, requiring vital theories in system, which stances boundaries for making nations like Vietnam, where reliance on imported batteries increases the taken a toll of electric vehicles and essentialness capacity systems (Boretti, 2023). These budgetary restrictions highlight the require for cost-effective materials and localized era to update openness (Sharma et al., 2025).

Common challenges are so also crushing, as the extraction of lithium and cobalt causes essential natural hurt, checking water and soil defilement in mining districts like South America and Africa (Mauger & Julien, 2017). Reusing remains inefficient, with around the world recovery rates underneath 5%, compounding resource deficiency and misuse collection (Ould Ely et al., 2019). The carbon impression of battery supply chains, from mining to manufacturing, help undermines the practicality of lithium-ion batteries, particularly in locale with obliged reusing establishment (Sharma et al., 2025). Tending to these challenges requires an all-enveloping approach, coordination attainable materials, capable reusing, and actually welcoming era shapes to ensure the long-term common sense of lithium-ion battery advancement.

Applications of Lithium-ion batteries

Lithium-ion batteries control a wide run of applications, with electric vehicles (EVs) being a basic driver of their ask. Nickel-manganese-cobalt (NMC) and lithium press phosphate (LFP) batteries run the show the EV publicize due to their tall essentialness thickness and security profiles, engaging companies like Tesla and BYD to provide vehicles with competitive ranges (Boretti, 2023). In any case, fulfilling driving ranges outperforming 500 km and fast-charging times underneath 15 minutes remains a challenge, pushing examine toward higher-capacity materials and moved forward charging establishment (Xu et al., 2023). The wide choice of EVs underscores the fundamental portion of lithium-ion batteries in diminishing transportation-related carbon outpourings.

Renewable essentialness capacity is another key application, as lithium-ion batteries stabilize control cross sections by putting absent essentialness from sporadic sources like wind and sun fueled (Blomgren, 2016). Large-scale wanders, such as Tesla's Megapack, outline the capability to store megawatt-hours of essentialness, but long-term sturdiness (>10 a long time) and gotten diminishment are essential for broader course of action (Sharma et al., 2025). These systems are basic for joining renewable essentialness into national systems, supporting around the world endeavors to combat climate alter.

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Common challenges are so additionally pulverizing, as the extraction of lithium and cobalt causes principal typical hurt, checking water and soil corruption in mining region like South America and Africa (Mauger & Julien, 2017). Reusing remains inefficient, with around the world recovery rates underneath 5%, compounding resource lacking and manhandle collection (Ould Ely et al., 2019). The carbon impression of battery supply chains, from mining to manufacturing, offer help undermines the common sense of lithium-ion batteries, particularly in locale with obliged reusing establishment (Sharma et al., 2025). Tending to these challenges requires an all-wrapping approach, coordination attainable materials, competent reusing, and truly welcoming period shapes to ensure the long-term common sense of lithium-ion battery movement.

Future Prospects

The longer term of lithium-ion batteries lies in making advanced materials to progress execution and practicality. Cobalt-free cathodes, such as LiMn2O4 and high-nickel NMC varieties, are picking up thought for their potential to diminish costs and normal influence, tending to the limitations of cobalt-dependent materials (Gopinadh et al., 2024). Silicon-carbon composite anodes and lithium metal anodes offer basically higher capacities than graphite, but issues like volume expansion and dendrite course of action require help ask almost to ensure consistent quality (Xu et al., 2023). Solid-state electrolytes, based on oxides or sulfides, ensure advanced security and essentialness thickness compared to combustible liquid electrolytes, in show disdain toward of the truth that moving forward ionic conductivity at room temperature remains a require (Sharma et al., 2025). These texture progressions, built up in inorganic chemistry, are essential for the taking after period of lithium-ion batteries.

Headways in manufacturing developments are so also basic for scaling battery era. Computerization and fake experiences (AI) are being facilitates to optimize battery arrange and streamline era, diminishing costs and headway timelines (Sharma et al., 2025). Normally neighborly creating shapes, such as those minimizing carbon surges, are additionally picking up balance to alter with around the world supportability goals. These mechanical headways will make lithium-ion batteries more open, particularly in creating markets like Vietnam, where localized generation might alter the essentialness scene.

Reusing and the establishment of a circular economy are crucial for tending to the characteristic challenges of lithium-ion batteries. Strategies like hydrometallurgy and arrange reusing can recover over 90% of battery materials, diminishing reliance on virgin resources (Ould Ely et al., 2019). Arranging batteries for basic destroying will development back reusing endeavors, especially in countries like Vietnam, where reusing establishment is youthful. These techniques are essential for minimizing misuse and ensuring resource supportability, altering with around the world endeavors to combat resource deficiency.

Elective battery chemistries offer promising pathways to outflank the controls of lithium-ion advancement. Lithium-sulfur (Li-S) batteries, with imperativeness densities around 500 Wh/kg, grant a high-capacity elective but persevere from down and out cycle life due to sulfur deterioration (Manthiram et al., 2014). Lithium-air batteries, conceivably coming to 1000 Wh/kg, go up against challenges in rechargeability and soundness but hold transformative potential for applications like electric flying (Girishkumar et al., 2010; Shao et al., 2013). Sodium-ion batteries, leveraging overflowing and low-cost materials, are well-suited for grid capacity, promoting a down to earth complement to lithium-ion systems (Sharma et al., 2025).

These rising innovations require critical investigate to attain commercial reasonability, but their improvement seem expand vitality capacity solutions. Collaboration between the academic community, industry, and government is basic to translate these headways into practical applications. In Vietnam, private ask approximately into materials, reusing, and elective chemistries can back businesses like VinFast and renewable imperativeness, reducing reliance on imports and developing conservative improvement. Universitys like TNUT can play a driving portion in driving improvement, ensuring that Vietnam contributes to the around the world move to clean vitality.

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II. CONCLUSION

Lithium-ion batteries remain the establishment of imperativeness capacity, in any case challenges in execution, security, and supportability ask nonstop advancement. Advances in inorganic materials and informative methods are shaping a future of higher-performing, more secure, and more doable batteries. In Vietnam, the transport of 34,855 electric cars and 72,468 electric bicycles by VinFast in 2023, adjacent a 20 GW renewable essentialness capacity, underscores the essential portion of lithium-ion batteries in electric vehicles and savvy grids (VinFast Auto, 2024; Xu et al., 2023). Be that because it may, reliance on imported materials and restricted reusing establishment require family ask almost. Teach similar to Thai Nguyen University of Technlogy can lead endeavors in making cobalt-free materials, solid-state electrolytes, and reusing propels, supporting Vietnam's green essentialness targets. Around the world collaboration and long-term wander will ensure lithium-ion batteries meet around the world and adjacent demands, driving doable essentialness courses of action around the world.

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