

A Review of Current and Future Energy Materials for the Construction of Lithium-ion Batteries

Hudson O. Eriki¹; Ferguson H. Tobins²;
Adiat I. Arogundade^{3*}; Abdulhakeem H. Nurudeen⁴

^{1,2,3,4}Department of Mechanical Engineering, University of Abuja, Nigeria

Corresponding Author: Adiat I. Arogundade^{3*}

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Abstract: This mini-review was performed to showcase the potential of lithium-ion batteries as key future energy-saving components for use in domestic, automobile, and other energy-demanding sectors. It explores the current and future energy materials that will transform the construction of Lithium-ion batteries, focusing on cathodes, anodes, electrolytes, and separators. It explores the critical advancement and challenges in the field of energy materials for lithium-ion batteries (LIBs), focusing on various components essential for improving battery performance. Different studies have shown that traditional cathode materials, primarily Lithium Cobalt Oxide (LiCoO₂), Lithium iron phosphate (LiFeO₄) and Lithium Manganese Cobalt Oxide (NMC) have dominated the market due to their favourable electrochemical properties. However, thermal instability and high costs necessitate the exploration of alternative materials like lithium-rich layered oxides and poly-anion compounds which enhance safety and energy density. The drive for cleaner energy is never over-emphasized, with the global shift from fossil-based fuels, more energy sources are investigated to find materials that are sustainable and durable in ensuring energy demands are met of which lithium-ion batteries are the primary source for such endeavour. Recently, the development of high-capacity materials such as lithium-nickel-cobalt-aluminum oxide (NCA) and advanced composite structures shows improved conductivity and structural integrity during the charge-discharge cycle. These innovations aim to balance performance with cost-effectiveness. This mini-review made available details of material composition, types of electrolytes, limitations and challenges of adoption for researchers, students and industry.

Keywords: Energy-Saving, Batteries, Lithium-ion, Composite Materials, Battery Capacity.

➤ Highlights

- The potential of lithium-ion batteries as key future energy-saving components,
- Thermal instability and high costs necessitate the exploration of alternative materials like lithium-rich layered oxides,
- Available details of material composition, types of electrolytes, limitations, and challenges of adoption for researchers, students, and industry.

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I. INTRODUCTION

Lithium-ion batteries have now become a growing energy source that fuels not only cell phones, laptops, and electric automobiles but also power grids. These batteries have numerous benefits over prior battery technologies, but they are still an innovation. While lithium battery discovery was in the 1970s, the first commercialized Li-ion battery was only introduced in 1991 by Sony [1]. Akira Yoshino made this possible, expanding on an earlier study by John Goodenough [1]. In recent years, the development of energy materials for LIBs has been given much attention, especially electrode materials. Meanwhile, Hang and Mekonne [2]

provide a summary of their findings and note that the works mentioned above emphasize that these materials largely determine battery productivity. In particular, Hang reports the most critical developments in new electrode materials, whereas Podlesnov et al.[3] work discusses the use of nanosized particles and co-polymerization in the modification of electrodes and electrolytes. Qi et al, [4] also address the developments of anode materials such as carbon, alloys, transition metal oxides, and silicon. The performance of lithium-ion batteries (LIBs) is significantly influenced by the choice of electrode materials as reported in a recent study [5] the research emphasizes the role of electrolytes, anodes, and cathodes in low-temperature performances. In addition, Li

underscores the importance of electrode materials' morphological structure in improving capacity, stability, and lifespan, the work also highlighted the significance of operating voltage in anode materials, and the potential of compositing with carbon nanomaterials. [6]. While Kim et al [6] reviewed how Complex Ti-based oxides have good safety performance and high cyclic stability for anode applications. The work also showed that compositing is an effective strategy to achieve comprehensively good electrochemical performance. The review emphasizes the importance of the relations among material composition, fabrication, structure, property, and lithium-ion battery performance; [7], [7]. The traditional graphite anode offers excellent cyclability but limited specific capacity. While graphite anodes offer good cyclability, their theoretical capacity (372 mAh/g) limits overall battery energy density [1]. Research focuses on high-capacity alternatives like silicon and lithium metal, but these materials suffer from volume changes during cycling, leading to electrode instability and capacity fade; [8]. Composite anode materials combining high-capacity materials and conductive scaffolds are being developed to mitigate this problem [9]. Research has shown that Cathode materials determine the cell voltage and capacity. Layered cathode materials like LiCoO_2 offer high energy density but suffer from cost limitations and stability concerns with cobalt [10]. Also, Olivine LiFePO_4 offers good safety and cyclability but lower energy density [11]. Intensive research is underway on high-nickel layered oxides and lithium-rich layered oxides for improved energy density while addressing stability issues [12]. Electrolyte is another important component of the LIBs as it facilitates lithium-ion movement between electrodes [13]. Conventional organic carbonate electrolytes are flammable; hence, limiting safety [14]. Solid-state electrolytes, based on polymers or ceramics, offer improved safety and potentially higher energy densities but face challenges like low ionic conductivity and inter-facial compatibility with electrodes [10],[15].

In addition, Organic liquid electrolytes are flammable and pose a safety risk in case of overheating or cell rupture [16]. During fast charging, lithium metal can deposit on the anode, potentially leading to dendrite formation (needle-like structures) that can pierce the separator and cause short circuits [17], [18]. Further challenges with the current LIBs include degradation caused by the repeated charging and discharging due to chemical and structural changes in electrodes, leading to capacity fade and reduced battery life [19],[20],[21]. Literature has shown that the current recycling processes are complex and energy-intensive, with limited efficiency for recovering valuable battery materials [21], [22]. A typical lithium-ion battery consists of three main components: a cathode, an anode, and an electrolyte as shown in Fig. 1.0. The cathode is typically made of a lithium metal oxide, such as lithium cobalt oxide (LiCoO_2), while the anode is usually composed of graphite. These materials are separated by a permeable membrane soaked in an electrolyte solution containing lithium salts [9], [23]. When the battery is charged, lithium ions move from the cathode to the anode through the electrolyte, this creates an external flow of electrons which generates an external circuit. [24]. As explained by Arumugam Manthiram et al., "Lithium-ion batteries charge and discharge by intercalating and de-intercalating lithium ions between two electrode materials [24].

This structure allows for reversible electrochemical reactions during charging and discharging cycles, making lithium-ion batteries a popular choice for portable electronic devices and electric vehicles [25]. As described by researchers at Stanford University, "The structure of a lithium-ion battery is like a layered cake." This layered configuration allows for efficient energy storage and release in lithium ion batteries [26]. Fig 1 shows the main construction of a typical Lithium-ion battery.

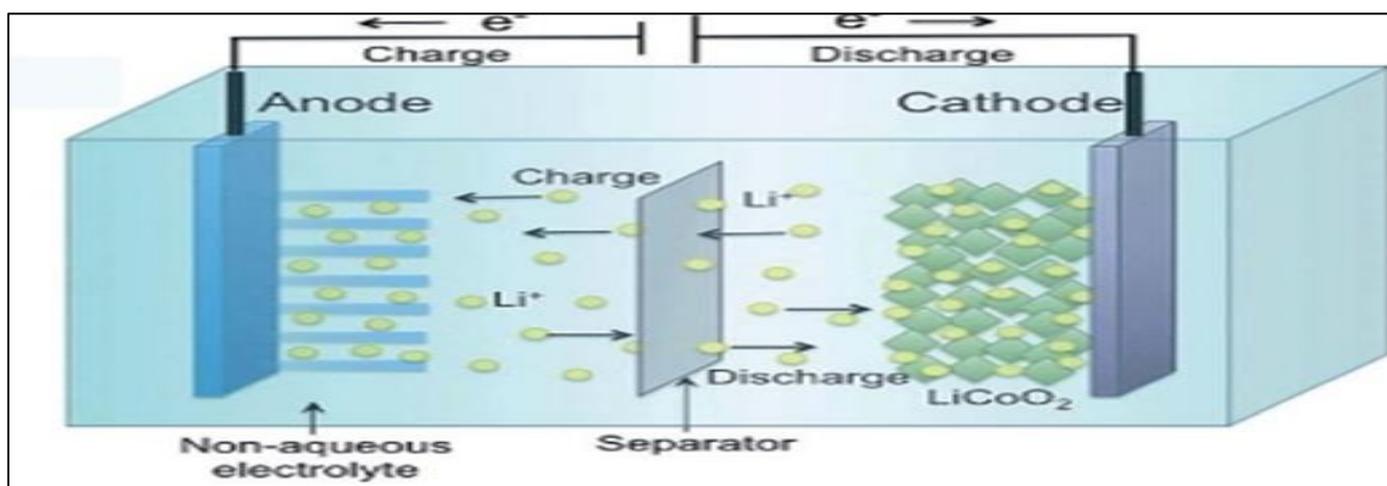


Fig 1: Structure of a Typical Lithium Battery[27],[28].

The future of LIB materials is focused on several key areas which includes improving energy density, enhancing cycle life, ensuring safety, reducing cost [29]. The performance of LIBs is intricately linked to the properties of the materials from which they are constructed [30].

Continuous advancements in electrode and electrolyte materials are crucial for unlocking the full potential of LIBs and enabling their broader application in the future of energy storage [31], [32].

II. TRADITIONAL CATHODE MATERIALS

The cathode materials used in lithium-ion batteries consist of lithium compounds, matrix compounds, and other materials [33]. The cathode's performance and characteristics of lithium-ion batteries including energy density, lifecycle, cycling stability, capacity, and rate performance are reliant on the cathode materials [34]. The paramagnetic or enhanced magnetic materials themselves are the soft cathode materials divided into layered and spinel materials [35], [36].

The use of conventional cathode materials is pivotal in advancing lithium-ion batteries, as they provide a suitable equilibrium between efficacy, affordability and environmental stability. Ongoing scientific studies are centered on upgrading the energy density, cycling resilience and safety attributes of such substances to meet the escalating requirements for dependable energy preservation solutions. As described in, [15], [37], [36] attention will be devoted towards exploring established cathode components including lithium cobalt oxide (LiCoO_2), lithium manganese oxide (LiMn_2O_4) and lithium iron phosphate (LiFePO_4), along with other traditional options that have been widely researched due to their electrochemical traits. The utilization of silicon-based materials was studied by Liu and Zhao, wherein they respectively analyzed a silicon core coated with metal oxide surface, and utilized silica fume combined with natural spherical graphite [36], [38]. Meanwhile, Graf conducted research on the use of lithium transition metal compounds. The work emphasized their capability to withdraw lithium ions during charging and also developed a carbon-coated Nano-metal oxide composite material [39].

In summary, these investigations demonstrate how conventional cathode substances can enhance the effectiveness of lithium-ion batteries [40]. The work of Chen et al [17] focuses on traditional cathode materials such as lithium cobalt oxide (LiCoO_2), lithium manganese oxide (LiMn_2O_4), and lithium iron phosphate (LiFePO_4) and other traditional materials that have been extensively studied for their electrochemical properties. The work of Jyoti et al showed that the development of electrode materials for lithium-ion batteries (LIBs) is another key area of research, with a focus on enhancing electrochemical performance [30].

LIBs can be categorized based on several parameters, one of which include the electrode materials. For negative electrode materials, carbon-based and lithium titanate (LTO, $\text{Li}_4\text{Ti}_5\text{O}_{12}$) are the most common materials [41].

In addition, for the positive electrode, most frequently utilized materials include lithium cobalt oxide (LiCoO_2), lithium-nickel oxide (LiNiO_2 or LiMn_2O_4) [30], [42]. Lithium iron phosphate (LiFePO_4) and lithium nickel manganese cobalt oxide (LiNiMnCoO_2), are two types of advanced rechargeable battery materials, other materials are lithium nickel cobalt aluminum oxide [43], [44]. The composition of the compound $\text{Li}(\text{Ni}_x\text{Co}_y\text{Al}_{1-x-y})\text{O}_2$ can be influenced by varying x and y , which represent specific alloys utilized by manufacturers [45]. The primary factor influencing the cost and performance of battery in terms of energy, power,

lifespan and safety is the cathode material. Safety can be related to the temperature at which the cell degrades beyond recovery in what is known as the thermal runaway; the highest temperature of the thermal runaway corresponds to the highest cell safety level. Lifespan is directly computed based on the number of cycles that a cell can withstand. The highest level of cell safety corresponds to the lifespan, which is directly calculated. The endurance is the maximum amount of cycling that a cell can endure, while performance indicates the conduct exhibited by the cell after undergoing such cycles. At extreme temperatures such as hot or cold, the capacities of cells are usually diminished [46]. Several researches have shown that doping with heteroatoms such as Al, Co, or Li can stabilize LiNiO_2 and improve its electrochemical performance, particularly during cycling [37], [42], [47]. This can be achieved through sol-gel methods, which have been shown to maintain the $\alpha\text{-NaFeO}_2$ type layered structure and increase discharge capacity [48], [49]. The work of Chen et al [47] show that doping with Ca, for example, can decrease Li/Ni disorder and enhance cycle stability and rate capabilities. In addition further research has shown that Al doping improves cycle performance at high temperatures while also enhancing cycling performance and stabilizing the host framework in Li-rich layered oxides [50], [47].

Co-doping with Ti and Co has been shown to improve the structural and thermal stability of Li_2RuO_3 [51]. Boron doping has been found to significantly reduce Li/Ni cation mixing in $\text{LiNi}_0.8\text{Co}_0.1\text{Mn}_0.1\text{O}_2$, leading to improved cycling stability and capacity retention [52], [53]. The improved performance via doping is attributed to the promotion of crystal growth and lattice ordering, as well as the reduction of surface oxygen defects [53], [54]. The enhanced electrochemical performance of the boron and aluminium-doped materials has widened the lithium diffusion channels through improved reversibility of the $\text{H}_2\text{-H}_3$ phase transition at 4.2 V [52].

A. Positive Electrode Lithium Materials.

➤ Lithium Cobalt Oxide (LiCoO_2):

Manjunatha and his team in [55] showed that LiCoO_2 cathode electrodes has a specific capacity and stable cycling performance, and hence it is currently most used as cathode materials in commercial LIBs. Understanding the electrochemical properties of LiCoO_2 is crucial before exploring enhancement approaches. The work of Cui [56] supported Al-doping and Li_2TiO_3 coating which enhances the electrochemical performance of LiCoO_2 at high voltage, Etefagh et al [57] also reported improved electrochemical properties in Al-doped Li-rich Mn-based oxides and Li_2MnO_3 [48].

According to Wang et al. [48] LiCoO_2 theoretical capacity reaches 274 mAh/g with excellent structural stability throughout charge-discharge cycles. To improve battery efficiency and longevity further, numerous studies have aimed to enhance the performance of LiCoO_2 cathodes. As Zhang et al noted in their review notes: "Lithium cobalt oxide has been extensively studied as a cost-effective cathode

alternative due to its good cycling stability." The researchers assert that it is crucial first to understand the electrochemical properties of LiCoO_2 thoroughly before exploring approaches such as doping with other elements, nano structuring or surface modification to boost said properties [15]. The drawbacks of LiCoO_2 , including thermal instability, potential toxicity, and limited availability, have prompted the search for alternative cathode materials [57]. Potential alternatives to LiCoO_2 include lithiated transition metal oxides, vanadium pentoxides, and polyanion-type materials [58]. These materials offer higher practical capacity and lower cost compared to LiCoO_2 . However, further research is needed to address their limitations, such as low discharge capacity and voltage [59].

➤ *Lithium Manganese Oxide (LiMn_2O_4)*

One promising cathode material that has gained attention in recent research is lithium manganese oxide (LiMn_2O_4). LiMn_2O_4 offers several advantages over other cathode materials, including high energy density, good thermal stability, and low cost. LiMn_2O_4 is a spinel structure material, with lithium ions occupying the tetrahedral sites and manganese ions occupying the octahedral sites [60], [55]. This unique structure allows for efficient lithium ion intercalation/deintercalation during charge and discharge cycles, leading to high electrochemical performance [40]. This further improves the rate capability and cycle stability of LiMn_2O_4 by designing a one-dimensional porous nanostructure. A range of studies have explored the impact of different synthesis methods and modifications on the electrochemical performance of LiMn_2O_4 as a cathode material in lithium-ion batteries. Zhao et al. in [61] found that the synthesis method significantly affects performance [62]. Ni'mah et al [62] demonstrates the successful application of LiMn_2O_4 synthesized from manganese ore as a cathode material. Its spinel structure allows Li-ion insertion/extraction without any phase transformations, resulting in negligible volume change, structural stability

during cycling, and, consequently, long cycle life. Numerous strategies have been proposed and validated by experiments to further enhance the battery performance of LiMn_2O_4 , including metal and non-metal doping, carbon coating, surface modifications/functionalization, hybridization, and the construction of copper-doped LiMn_2O_4 . Surprisingly, during the last three years, only one review article has been published focusing on the crystal structure and synthesis strategy of LiMn_2O_4 .

The work of Ting et al [63] showed that the modification of LiMn_2O_4 improves its electrochemical performance. The study shows that modification by coating is crucial for enhancing the electrochemical performance of LiMn_2O_4 . Surface coating with oxides and monoxide substances reduces surface area, preventing side reactions with the electrolyte and decreasing Mn dissolution during cycling tests. LiMn_2O_4 , particularly the modified version, is the leading cathode material for power lithium-ion batteries and represents the future trend in cathode material development. Additionally, the use of nano-structured and nanosized LiMn_2O_4 particles has shown promising results in increasing specific power for high power applications such as electric vehicles [64].

➤ *Lithium Iron Phosphate (LiFePO_4)*

Lithium iron phosphate has gained significant attention as a promising cathode material for lithium-ion batteries due to its unique properties such as high thermal stability, excellent electrochemical performance, and abundant availability of raw materials [44]. One of the key advantages of lithium iron phosphate as a cathode material is its high thermal stability compared to LiCoO_2 and other cathode materials [65]. According to Popovic [66] LiFePO_4 has a high stable trypillite structure which could be artificially synthesized using conversion solid state method.

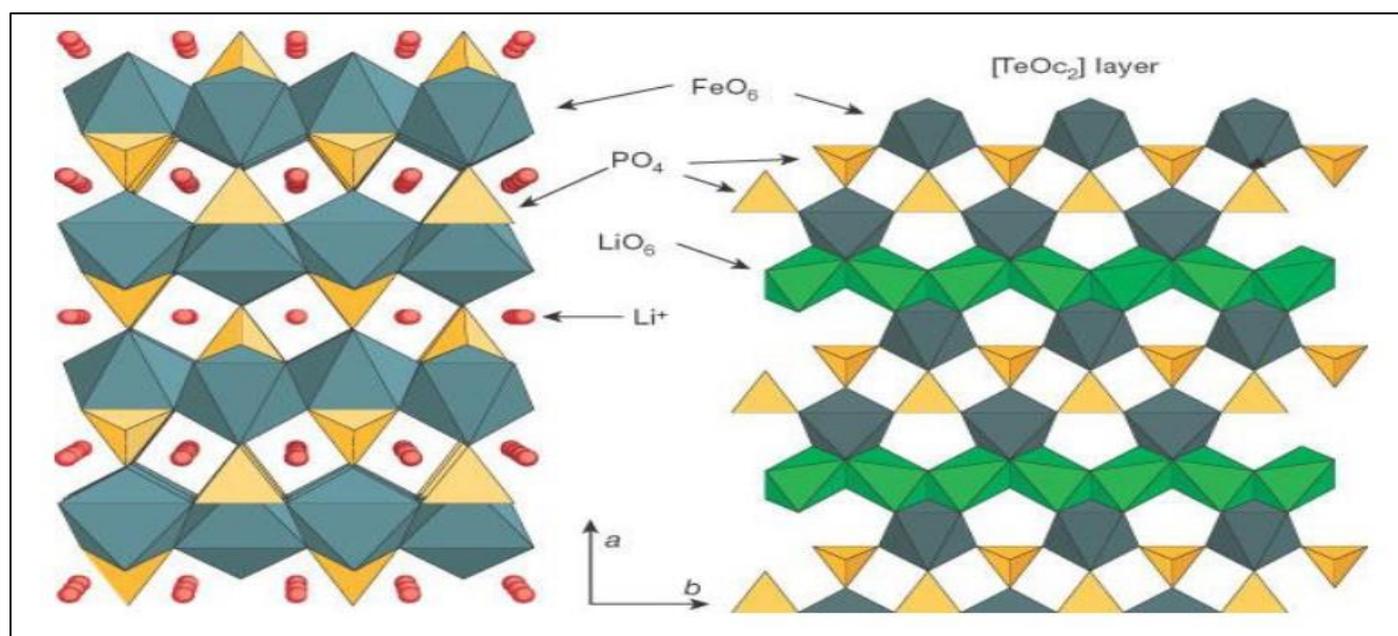


Fig 2: Structure of LiFePO_4 [66].

Lithium iron phosphate (LiFePO₄) is a reversible cathode material for use in lithium-ion batteries that has been considered as a cathode material due to its low cost, good thermal stability, safety, and excellent cycle life. Unlike other cathode materials (metal oxides), the structure of LiFePO₄ belongs to olivine rather than spinel, providing a 3D interconnectivity with FeO₄ units in the lattice [67].

Studies have demonstrated that LiFePO₄ exhibits excellent rate capability and cycling stability, making it an ideal candidate for high-power applications such as electric vehicles and grid energy storage systems [40]. The unique crystal structure of LiFePO₄ allows for fast lithium ion diffusion, resulting in enhanced charge/discharge efficiency and reduced capacity fade over extended cycling [36]. The crystal structure of LiFePO₄ consists of interconnected phosphate tetrahedral that provide a stable framework for hosting lithium ions during electrochemical reactions [66]. Additionally, the presence of Fe²⁺/Fe³⁺ redox couples in the structure enables reversible lithium intercalation/deintercalation processes without phase transitions or structural degradation [40]. Research efforts are also focused on enhancing the conductivity and optimizing the particle size distribution of LiFePO₄ nanoparticles to further improve battery performance [36].

➤ *Lithium Nickel Manganese Cobalt Oxide (LiNiMnO₂)*

Studies have shown that LiNiMnO₂ cathodes exhibit high specific capacities, typically ranging from 150-200 mAh/g, making them ideal for high-energy density applications [48]. Additionally, LiNiMnO₂ cathodes have demonstrated excellent cycling stability with minimal capacity fade over hundreds of cycles [34]. This can be attributed to the stable crystal structure of LiNiMnO₂, which allows for efficient lithium ion insertion/extraction during charge/discharge cycles [53]. According to a study [47] LiNiMnO₂ cathodes show great promise for use in lithium-ion batteries due to their high capacity, excellent cycling stability, and improved safety features.

➤ *Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO₂)*

One promising cathode material that has gained significant attention in recent years is Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO₂). LiNiCoAlO₂ is a ternary oxide compound which belongs to the class of layered structure materials, similar to other popular cathode materials such as Lithium Cobalt Oxide (LCO) and Lithium Iron Phosphate (LFP). It offers several advantages over traditional cathode materials, including higher specific capacity,

improved thermal stability, and better rate capability [39], [68]. The combination of nickel, cobalt, and aluminum in LiNiCoAlO₂ provides a balanced compromise between energy density and power density, making it suitable for both consumer electronics and electric vehicle applications [69]. One of the main advantages of LiNiCoAlO₂ is its high specific capacity, typically around 200-220 mAh/g. This high capacity allows for longer runtime and increased energy storage compared to other cathode materials [50]. Additionally, LiNiCoAlO₂ exhibits good cycling stability and low self-discharge rates, resulting in longer lifespan and improved overall performance of lithium-ion batteries. Furthermore, LiNiCoAlO₂ has shown excellent thermal stability at elevated temperatures, reducing the risk of thermal runaway and enhancing safety during operation. Despite its numerous advantages, LiNiCoAlO₂ also faces some limitations and challenges that need to be addressed for widespread commercial adoption. One notable drawback is the cost associated with using cobalt in the composition of LiNiCoAlO₂. Cobalt is a relatively expensive element with limited global reserves, leading to concerns about supply chain sustainability and cost implications for large-scale battery production. Moreover, LiNiCoAlO₂ electrodes may suffer from structural degradation upon extended cycling, which can affect the overall performance and efficiency of lithium batteries [20],[70].

B. Performance Comparison of Traditional Cathode Materials

The performance comparison of LiCoO₂, LiMnO₄, LiFePO₄, LiNiMnCoO₄, and LiNiCoAlO₄ as cathode materials used in lithium batteries reveals varying degrees of efficiency and stability. According to a study [71] LiCoO₂ is known for its high energy density but has limited cycle life due to cobalt dissolution. On the other hand, LiMnO₄ offers better safety features but suffers from lower capacity and voltage compared to other materials. LiFePO₄ exhibits excellent thermal stability and longer cycle life but has a lower energy density [72]. Furthermore, LiNiMnCoO₄ shows promising results with high capacity and improved cycling performance, while LiNiCoAlO₄ demonstrates good rate capability and stable cycling behavior [73]. However, it is important to note that each material has its own set of advantages and drawbacks when used as cathodes in lithium batteries.

Table 1 shows the performance comparison of the traditional cathode materials based on their energy density, cycle life and safety.

Table 1: Relative Properties of Traditional Lithium Cathode Materials

Cathode Materials	Energy Density	Cycle life	Safety	Voltage capacity	Cost
LiCoO ₂ [74]	High	Poor	Thermal runaway Problem	High	High
LiMn ₂ O ₄ [75]	High	Good	Good safety	Low	Low
LiFePO ₄ [76]	Low	Very Good	High Thermal Stability, [77]	Low	Moderate
Li(NiMnCo)O ₂ [78]	High	Good	High Thermal Stability	High	High
Li(NiCoAl)O ₂ [79]	Low	Excellent	High Thermal Stability	High	High

The choice of cathode material should be based on specific requirements such as energy density, cycle life,

safety, and cost-effectiveness. Further research and development are needed to optimize these materials for better

performance in lithium batteries. Depending on the chemical properties of the materials of the battery, terminal voltages and energy densities of the battery varies. Table 2 shows the

comparison of terminal voltage and energy density of LiCoO_2 , $\text{Li}(\text{NiCoAl})\text{O}_2$, $\text{Li}(\text{NiCoMn})\text{O}_2$, LiMn_2O_4 , LiFePO_4 .

Table 2: Electrochemical Parameters of Several Cathode Materials [75].

Cathode material	Voltage (Vol)	Energy Density(gcm^{-3})	Specific Energy (Whg^{-1})	Specific Capacity (mAhg^{-1})
LiCoO_2	3.90	5.10	0.98	294
LiMn_2O_4	4.05	4.31	0.56	148
LiFePO_4	3.50	3.60	0.59	169
$\text{Li}(\text{NiCoMn})\text{O}_2$	3.60	4.85	0.98	274
$\text{Li}(\text{NiCoAl})\text{O}_2$	3.60	3.60	1.02	284

The use of intercalation cathode materials is one major advancement in Lithium-ion batteries. Intercalation cathode is a solid host network which can store guest ions. These intercalation compounds can be divided into several crystal structure such as a layered, spinel, olivine and tsavorite as shown in Fig. 3. Most current intercalation cathode research

is focused on the transition metal oxide and polyanion compounds due to their higher operating voltage and resulting higher energy storage capability. A typical intercalation cathode have 100 - 200 mAh/g specific capacity and 3-5 V average voltage vs Li/Li^+ as shown in Figure 3.

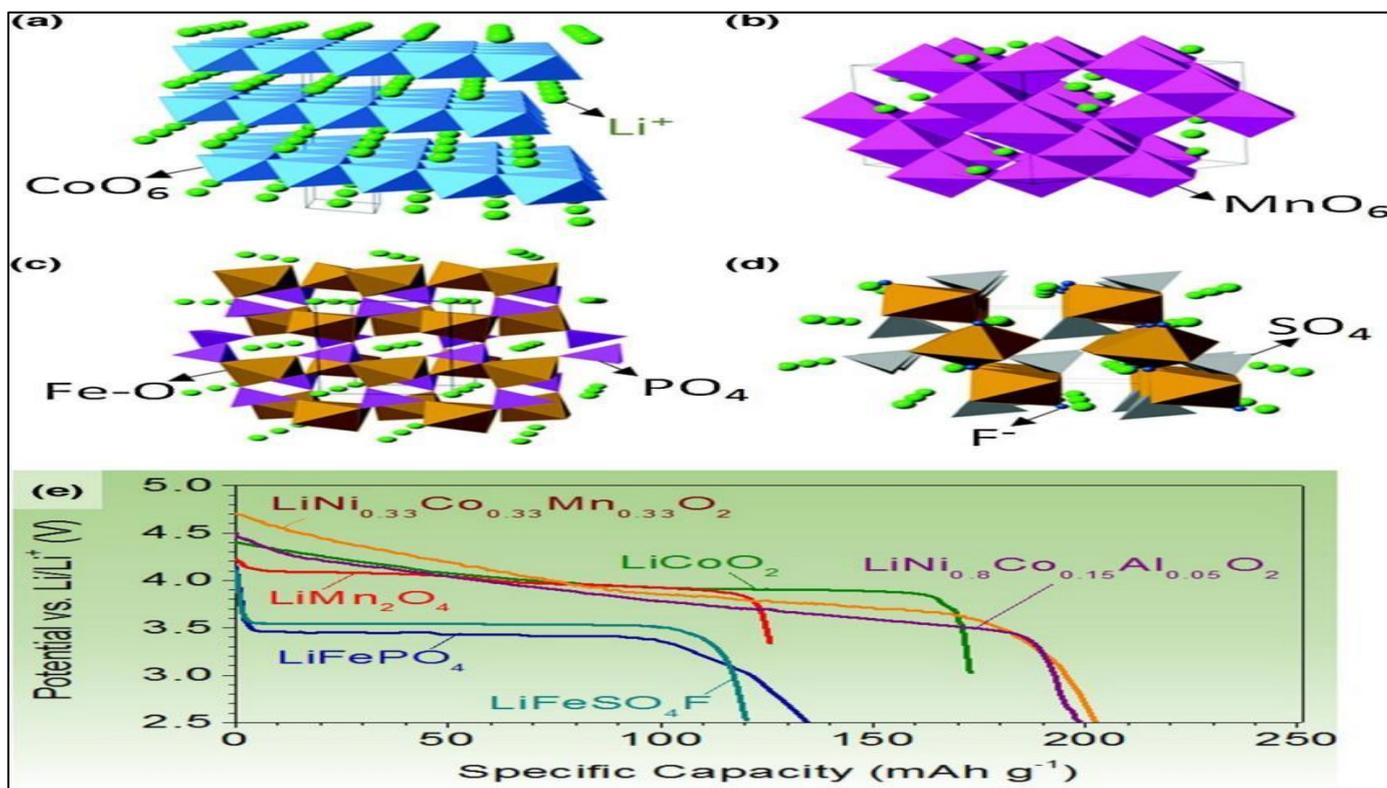


Fig 3: Crystal Structure and Discharge Profiles of Representative Intercalation Cathodes. Structure (a), Layered (LiCoO_2)., (b) Spinel (LiMn_2O_4), (c) Olivine (LiFePO_4), (d) Tsavorite (LiFeSO_4F), (e) Typical Discharge Profile of Intercalation Cathode [80].

C. Negative Electrode Lithium Materials (Anode Materials)

A recent report shows that anode materials play a critical role in determining the performance and lifespan of lithium-ion batteries [81]. Generally, anode materials contain energy storage capability, chemical and physical characteristics which are very essential properties that depends on size, shape as well as the modification of anode materials. Key requirements for optimal anode materials are high specific capacity, high specific conductivity, structural stability, long cycle life, safety, cost-effectiveness, compatibility and good Environmental Impact [82].

➤ High Lithium-Ion Diffusion Coefficient.

Some researchers have argued [5],[83] that a critical property for anode materials in the construction of LIBs is the Lithium-Ion Diffusion Coefficient (Li-ion diffusivity),. A high Li-ion diffusivity allows lithium ions to quickly intercalate (insert) and de-intercalate (extract) from the anode structure[84].

Another study [85] shows that this translates to faster charging and discharging rates, making the battery more responsive to power demands. This is especially crucial for applications like electric vehicles that require rapid charging

capabilities. High Lithium ion diffusion coefficient results in improved rate capability and also maintains structural integrity [86]. Eftekhari [87] analyzed the effect of rate capability, which is the battery's ability to deliver its rated capacity at high current densities. According to this study, a high Li-ion diffusivity ensures efficient lithium-ion transport even at faster charge/discharge rates. This minimizes polarization effects, which can lead to voltage drops and reduced capacity at high currents. During cycling, lithium ions entering and exiting the anode can cause volume changes. A slow Li-ion diffusivity can lead to uneven lithium distribution within the anode, creating mechanical stress. This stress can lead to the formation of cracks and ultimately, capacity fade – the gradual loss of capacity over charge cycles. A high diffusivity promotes uniform lithium distribution, mitigating stress and improving cycling stability, [88]. Further research in [9],[89] show that a high Li-ion diffusion coefficient is a key performance parameter for anode materials in LIBs. It facilitates faster charging/discharging, enhances rate capability, and promotes better cycling stability. The work of Mustafa et al [90] showed that as research delves into next-generation batteries with even higher energy densities, the development of anode materials with exceptional Li-ion transport properties will remain a central focus.

➤ *Types of Anode Materials*

• *Graphite Anode*

Graphite remains the dominant anode material in commercially available lithium-ion (Li-ion) batteries due to its unique combination of properties [91]. This review explores the structure of graphite and its key properties that make it a suitable anode material for Li-ion batteries. The work of Ji et al [92] shows that graphite possesses a layered crystalline structure composed of stacked graphene sheets. Each graphene sheet consists of a network of carbon atoms arranged in hexagonal rings. The key feature for Li-ion intercalation is the weak van der Waals forces between these graphene layers, allowing for the reversible insertion of lithium ions. In addition, Jannes et al [93] revealed how high theoretical capacity, excellent cyclic stability, good electrical conductivity, natural abundance and affordability are properties that make graphite a good anode material in LIBs. The use of graphite anode have some limitations which includes first cycle irreversible capacity, lower theoretical capacity compared to newer materials and slow kinetics at high rates [94]. The best anode material of commercially viable lithium-ion batteries is Graphite, which is mainly low-cost, low-toxicity, and high-abundant therefore mostly used in batteries of electronic devices, electric transportation, and grid-based storage. The physical and electrochemical characteristics of graphite anodes have been researched in depth. Nevertheless, there are still doubts regarding the electronic structures and whether the electrons remain in localized states on Li, delocalized states on C, or a mixture of both. In this context, electron paramagnetic resonance (EPR) spectroscopy is the most sought-after and vital tool for one to observe the electronic states brought about by electrochemical cycling because it accomplishes the measurement of the properties of the unpaired electrons in

lithiated graphite,[1]. In these studies, ex situ variable-temperature (10–300 K), variable-frequency (9–441 GHz) EPR was carried out to draw out the g tensors and line widths and to explain the effect of metallicity on the observed EPR spectra of electrochemically lithiated graphite at four different states of lithiation [92],[95]. The results have shown that the higher resolution given by EPR at the high frequencies (300GHz or more) allows the observation of up to three distinct electron environments of axial symmetry, the actual situation and the hyperfine coupling to the neighbouring Li nuclei. In addition, Insinna and his team illustrated the use of EPR spectroscopy in the study of the local electronic structure of graphite at various lithiation stages, which is a key technology for this technology to be used for screening and detecting the possible new materials for their application in Li-ion batteries [90], [93]. One of the main problems with the pristine graphite anode is its slow charging and low energy density. In order to overcome these issues, scientists are working on various techniques like surface modifications and composite electrodes.

• *Silicon Anode*

Silicon (Si) emerges as a promising alternative due to its significantly higher theoretical capacity, potentially enabling batteries with much longer range [96]. Silicon boasts a theoretical capacity exceeding 4,200 mAh/g, compared to graphite's 372 mAh/g [97]. This tenfold increase translates to the potential for batteries with significantly higher energy density, a critical requirement for long-range EVs. Additionally, silicon is abundant and relatively inexpensive. Despite its advantages, silicon presents significant challenges that have hampered its widespread adoption. Large Volume Change is one of the limitations of silicon anode. The work of Matthew et al in [98] showed that during lithium ion insertion and removal, silicon experiences a substantial volume change (around 300%). This drastic expansion and contraction can cause the electrode to crack and lose electrical contact, leading to rapid capacity fade and a shortened lifespan. Another limitation of Silicon Anode is the Solid Electrolyte Interface (SEI) Instability. The formation of the SEI layer, a passivation film on the electrode surface, is crucial for battery operation. However, the large volume changes in silicon can cause the SEI to repeatedly break and reform, consuming electrolytes and further reducing battery performance [65]. Researchers are actively exploring strategies to address the challenges of silicon anode through the development of Nano-structured silicon, composite electrodes, surface modifications and electrolyte additives.

• *Metal Oxide Anodes*

Metal oxides hold immense promise for next-generation LIB anodes due to their high theoretical capacities [99]. The work of Bouibes and his team in,[100] showed that the Transition Metal Oxides including materials like SnO₂, Co₃O₄, NiO, Fe₃O₄, and MnO₂, offer high theoretical capacities ranging from 600 mAh/g to 1000 mAh/g [101], [102]. However, challenges include significant volume changes during lithium insertion/removal, leading to electrode instability and capacity fade. In addition, there is the Spinel Oxides, exemplified by Li₄Ti₅O₁₂ (LTO), which exhibits excellent cyclability and structural stability due to

their rigid spinel framework [103],[104]. While LTO boasts a lower theoretical capacity (around 175 mAh/g) compared to other TMOs, its exceptional cycle life and high-rate capability make it attractive for applications requiring fast charging and long lifespan, [9].

➤ *Techniques for Improving Anode Performance*

Researchers are actively exploring various strategies to improve the overall performance of anode materials. This includes Nano structuring which involves fabricating materials like Si and metal oxides into nanostructures (nanoparticles, nanowires) that reduces the volume change experienced during lithium ion cycling and shortens diffusion paths, leading to improved capacity and cyclability. The use of Composite Electrodes is also employed by combining high-capacity materials with conductive materials like carbon nanotubes or conductive polymers which creates composite

electrodes [105],[106]. These composites address issues like mechanical instability (Si) and improve overall electrical conductivity.

Doping and Surface Modifications are other methods which involves introducing foreign atoms or functional groups into the electrode material to enhance lithium ion storage, improve cyclability, and promote the formation of a stable SEI layer [107]. Electrolyte Optimization has also been employed. This involves developing new electrolytes with higher ionic conductivity and improved compatibility. With high-anode capacity materials, optimized electrodes can further enhance battery performance [108],[109]. Table 3 compares the voltage, specific capacity, and energy density of different anode materials for lithium-ion batteries. The values are approximate and may vary depending on the specific material composition and cell design.

Table 3: Comparison of Different Anode Materials [108], [4].

Anode Material	Voltage (V)	Specific Capacity(mAh/g)	Energy Density (Wh/kg)
Graphite	0.1 -0.2	372	372
Silicon	0.1 -0.5	3579	1000 – 2000
Lithium Titanate (Li ₄ Ti ₅ O ₁₂)	1.5	175	175
Tin (Sn)	0.1 -0.8	994	660
Germanium (Ge)	0.3- 1.1	1600	1160
Antimony (Sb)	0.8-0.9	660	440

The future of Li-ion battery anodes lies in pushing the boundaries of theoretical capacity while addressing practical limitations. Emerging trends like exploring high-capacity materials, utilizing nano structuring and composite design, and optimizing electrolytes hold immense promise for achieving next-generation Li-ion batteries,[12]. With a focus on sustainability and scalability, these advancements can pave the way for a more sustainable future powered by high-performance and long-lasting Li-ion batteries,[110].

III. ELECTROLYTE MATERIALS FOR LITHIUM-ION BATTERIES

An electrolyte is a chemical substance which serves as an ion transformation medium in a lithium-ion battery, it may be solid, liquid, or a mix of both. The ideal electrolyte for a Lithium-ion battery should have several specific properties such as thermal stability, non-toxicity, environmental adaptability, sufficient ionic conductivity, electrochemical stability etc; [111], [112].

A. *Types of Electrolytes*

A rechargeable lithium-ion battery typically comprises any of the two types of electrolytes, the first group are liquid-based electrolytes and the second group is regarded as solid-state electrolytes; [110].

➤ *Liquid-based Electrolytes*

Liquid electrolytes are the most commonly used in commercial lithium-ion batteries. They typically consist of lithium salts dissolved in organic solvents. The choice of electrolyte has a significant impact on the performance and safety of the battery. Some key considerations for liquid electrolytes include but are not limited to; High ionic

conductivity to enable fast Li-ion transport,[113] wide electrochemical stability window to allow high voltage operation, low viscosity for efficient transport of ions and electrons, compatibility with electrode materials and ability to form a stable solid electrolyte interphase (SEI),[114] safety and environmental friendliness; [115], [60], [116]. Commonly used lithium salts include LiPF₆, LiBF₄, LiClO₄, and LiTFSI. Organic solvents like ethylene carbonate (EC), dimethyl carbonate (DMC), and diethyl carbonate (DEC) are widely employed. Recent research has focused on developing electrolyte additives to improve performance and safety. For example, vinylene carbonate (VC) and fluoroethylene carbonate (FEC) are commonly used as SEI-forming additives to stabilize the anode-electrolyte interface;[113], [117].

➤ *Solid-State Electrolytes*

Solid-state electrolytes have attracted significant attention as a safer alternative to flammable liquid electrolytes. They can enable the use of lithium metal anodes and provide better thermal stability. Promising solid-state electrolyte materials include inorganic ceramics like Li₁₀GeP₂S₁₂ (LGPS), Li₇La₃Zr₂O₁₂ (LLZO), and Li_{1.3}Al_{0.3}Ti_{1.7}(PO₄)₃ (LATP), polymer-ceramic composites like PEO/LLZO and PVDF/LLZTO, and sulfide-based glasses like Li₂S-P₂S₅ and Li₂S-SiS₂; [118], [119]. Key requirements for solid-state electrolytes include high ionic conductivity at room temperature (>10⁻⁴ S/cm), wide electrochemical stability window, compatibility with electrode materials, mechanical robustness, and scalable synthesis;[120], [121]. Challenges include improving ionic conductivity, interfacial compatibility, and mechanical properties;[122], [123].

➤ *Polymer Electrolytes*

Polymer electrolytes are an emerging form of solid-state electrolytes which combine the advantages of liquid and solid-state electrolytes. They can provide good mechanical properties, flexibility, and safety while enabling high ionic conductivity. Shin et al, [124] show that the common polymer hosts include polyethylene oxide (PEO), polyvinylidene fluoride (PVDF), and polymethyl methacrylate (PMMA). Lithium salts like LiPF₆, LiBF₄, and LiTFSI are typically added to provide Li-ions. Strategies to improve ionic conductivity include using plasticizers or ionic liquids, incorporating ceramic fillers like Al₂O₃, SiO₂, and TiO₂, and designing block copolymers with Li-ion conducting domains; [114], [125], [126]. Challenges include achieving high ionic conductivity at room temperature and improving mechanical properties and stability [114]. Hybrid polymer-ceramic composites and solid-polymer-gel electrolytes are promising approaches. In summary, the choice of electrolyte is crucial for lithium-ion battery performance and safety. Liquid, solid-state, and polymer electrolytes each have their own advantages and challenges. Ongoing research aims to develop electrolytes with high ionic conductivity, wide stability window, and excellent compatibility to enable the next generation of high-energy and safe lithium-ion batteries.

IV. CHALLENGES AND LIMITATIONS OF ENERGY MATERIALS

Lithium-ion batteries have become so indispensable in portable electronics due to their high energy density and long cycle life. However, their widespread adoption for electric vehicles and grid storage faces challenges related to material limitations in three key areas: capacity fade, safety considerations, and cost; [127],[128].

A. *Capacity Fading*

➤ *Lithium-Ion Batteries Can Experience Capacity Fading Over Time Due to Several Factors. these Include:*

- Degradation of the anode and cathode materials, such as structural changes and loss of active material,
- Electrolyte decomposition and formation of solid-electrolyte interphase (SEI) layer, which consumes lithium ions [107].
- Volume changes in the anode (e.g. silicon) during lithiation /de-lithiation, leading to cracking and loss of contact [129].
- Transition metal dissolution from the cathode, which can deposit on the anode and increase impedance [130].

B. *Safety Considerations.*

Safety is a major concern for lithium-ion batteries, which can experience thermal runaway reactions leading to fire and explosion under the following conditions: Overcharge or over-discharge can cause lithium plating, dendrite growth, and internal short circuits [131]. In addition, mechanical abuse such as puncture, crush, or impact can also trigger internal short circuits [132]. Thermal abuse from external heating or internal heat generation can also lead to

the decomposition of electrolyte and electrode materials [129].

C. *Cost Considerations*

The high cost of lithium-ion batteries is a barrier to widespread adoption, especially for electric vehicles, key cost drivers include [130], [133]:

- Expensive raw materials like cobalt, nickel, and lithium
- Complex manufacturing processes and battery pack assembly
- Low production volumes compared to demand, limiting economies of scale.

Addressing these challenges through innovations in battery materials, cell design, and manufacturing processes are crucial to enabling the widespread adoption of lithium-ion batteries for transportation and grid-scale energy storage applications [134].

V. STRATEGIES FOR ENHANCING BATTERY PERFORMANCE

There is a constant push to improve the performance of Lithium-ion batteries in terms of capacity, lifespan, safety, and charging rates. This review explores key strategies for enhancing LIB performance across three main areas: material design and synthesis, electrode architecture and morphology, and electrolyte optimization [133].

A. *Material Design and Synthesis*

➤ *Several Material Design Strategies can be Employed to Improve Lithium-Ion Battery Performance. these Include:*

- Reducing the dimensions of active materials, such as using nanostructures, can shorten Li-ion and electron transport pathways [77].
- Forming composites with conductive additives like graphene can enhance charge transport. Graphene is a powerful planar conductive additive, which is considered to be one of the most promising conductive additives due to its unique physicochemical properties including high aspect ratio, chemical resistance, excellent conductivity, and low dosage of effective characteristics [135].
- Doping and functionalization of active materials can optimize their electrochemical properties [136].
- Tuning the particle morphology can improve packing density and accessibility of active sites [90].
- Coatings or shells around active materials can protect against side reactions and improve stability [80].

Si-based electrode technology is a widespread option implemented to increase the electrochemical performance of Si-based anodes, which aims mainly at both the cyclic stability and the capacity of the electrode. One of the most effective methods is using Si/C composites where Si is the high capacity active material and the carbon matrix is the key material that buffers the volume expansion, enhances the electrical conductivity, and stabilizes the SEI layer [135], [136], [137]. Further, the invention of these structures

through different methods like, for example, producing them by chemical or physical vapor deposition and atomic layer deposition on a substrate, followed by the thermal treatment, performance analysis, and comparison, has been known to have an impact on their characteristics and utility. However, new approaches are now being developed to synthesize nanostructured Si materials such as producing them by chemical or physical vapor deposition and atomic layer deposition on a substrate, following the thermal treatment, performance analysis, and comparison of these nanostructured Si material characteristics and utility. The nanomaterials with one dimension are those where the length is in the nanoscale while the other two dimensions are in the micro-scale. The nanomaterials with two dimensions, such as defect-rich sheets that have metal particles decorating the edges and the surface oxidation forming thin layers on the walls, are the products of these methods. The composition of these materials can be arranged from both two-dimensional and three-dimensional directions, which means that the bands can be folded and filled up with other components.

A key element of the improvement of silicon-based anodes for LIBs is the fabrication of Carbon - Si composites [139],[140]. 1D carbon materials such as carbon nanofibers (CNFs) and carbon nanotubes (CNTs) are the major types that have received a lot of attention due to their use in manufacturing LIBs. The Si composition with either CNTs or CNFs produces more electrical conductivity, super mechanical and thermal stability [141], [88].

Methods like electrode etching, self-assembly, and chemical vapor deposition have led to the development of Si nanostructures with improved porosity and electrode architecture; [88], [143]. These structural modifications has significantly reduced the problem of excessive volume expansion of silicon. Recently Si and carbon (Si/C) blending has become a promising prospects for anode materials based on the improved mechanical properties of the composite; [81], [143].

In addition, the use of Artificial Solid Electrolyte Interphase (ASEI) for Si anode has helped to boost the performance of lithium-ion batteries. The naturally formed SEI is often brittle and heterogeneous rendering it susceptible to cracking or delamination over the battery's lifespan, which in turn causes more dissipation of lithium ions and hence which leads to capacity fade and also raises safety concerns by uneven plating of lithium and the eventual dendrite growth [144]. This decrease in stability not only increases the weak spots of the anode where the electrolyte can attack, but also causes safety hazards because the uneven lithium plating can cause lithium plates to grow unevenly into dendrites. This can result into short-circuit and eventually battery failure. Reducing SEI formation by artificial methods is an antidote of battery failure, particularly in high-capacity anodes like Si that undergo the largest volume changes during the cycling of the cells; [88], [145]. Such ASEIs, which are typically applied ex-situ, are developed to form more resistant and stable protective layers as compared to the naturally formed SEI, providing a more robust and stable protective layer compared to the naturally formed SEI. Indeed, these tactics can have

different impacts. For instance, the first method tackles both electrolyte and the SEI in the formation and stability of SEI, while the second method takes particular aim at the electrolyte-related problems of SEI [146].

B. Electrode Architecture and Morphology.

These include the use of nano-structured electrodes, composite electrodes and high-porosity electrodes. Fabricating electrodes with nanostructured materials can significantly improve their performance. Nanoparticles offer shorter lithium ion diffusion paths, leading to faster charge/discharge rates and better capacity utilization [137], [77]. Creating composite electrodes by incorporating conductive additives (like carbon) into the electrode material improves electrical conductivity and reduces electrode-electrolyte resistance [138], [139].

Electrode architecture involves the production of electrodes having high porosity to obtain a stronger penetration of the electrolyte and thus to enable lithium ions movement in the electrolyte district have unparalleled rate capability and increased cycle life. The use of organic material also improves Lithium-ion battery performance. the work reported in, [151], [88] illustrates a method in which anode particles are coated with organic materials such as citric acid, polyacrylic acid (PAA), or a carboxymethyl cellulose-citric acid (CMC/CA) composite. Such coatings may be used to improve the mechanical strength of the SEI and to improve the electrochemical stability of the system. The pre-lithiation of the anode material is one of the most effective tactics to enhance the performance of LIBs, especially when dealing with high-capacity anodes like silicon [152], [153].

One of the most prominent methods for reabsorbing the lithium ion that was initially lost to SEI in a lithium battery is through the pre-lithiation process. This defect is most prominent with electrolytes of lower quality. The innovative strategy of pre-lithiation deals with such problems as low coulombic efficiency and the need for enhanced electrical conductivity, respectively, which results in greater practical use for Si-based anodes; [88], [154]. A lot of issues have been solved by pre-lithiation methods. Methods that have been used for pre-lithiation are the LFC, SLMP, and chemical process which are the primary ones. These techniques have been implemented to stop lithium losses. Literature have shown that the electrochemical performance has been boosted by improving the ICE and rate performance; [139].

Advanced Composite electrodes is another approach that have been used to improve lithium-ion batteries as reported in, [155],[151]. While the blending of Si with carbon in 1D, 2D, and 3D configurations has shown remarkable improvements in conductivity and structural integrity, there is substantial scope for the development of novel composite structures [156], [7]. This can be achieved by hybrid materials that can take the advantages of carbons conductivity and also introduce new elements that could buffer effect of excessive expansion of silicon resulting in an increase in electrode/electrolyte interface stability; [88].

C. Electrolyte Optimization.

The Electrolyte optimization method involves altering the composition of the electrolyte to promote the formation of a more robust and uniform SEI layer. The electrolyte plays a key role in lithium-ion battery performance. The various strategies for optimization include: Modifying the electrolyte composition and additives to improve ionic conductivity and stability. Other methods are developing solid-state electrolytes to enable the use of high-capacity lithium metal anodes, and engineering the solid-electrolyte interphase (SEI) layer to protect the electrolyte and enable stable cycling,[131], [140], [141]. For instance, the introduction of additives like gamma-butyrolactone in traditional electrolytes can selectively dissolve lower-modulus components of the SEI, resulting in a layer predominantly composed of lithium fluoride and polycarbonates [142]. This novel approach has shown promising results, with raw micron-sized Si anodes retaining 87.5% capacity after 100 cycles at 0.5 C (1500 mA g⁻¹, 25 °C) [104],[143]. A multi-pronged approach targeting the active materials, electrode architecture, and electrolytes is needed to significantly enhance lithium-ion battery performance for advanced applications like electric vehicles. For example, modifying the LiMn₂O₄ cathode with ultrasonic-assisted electrochemically synthesized graphene was shown to enhance lithium-ion battery charging performance [144].

VI. RECENT ADVANCES IN ENERGY MATERIALS

This review explores recent advancements in three key areas of LIB materials. These include nano-structured materials, composite electrodes, and high-energy density materials.

A. Nanostructured Materials

Recent advances in lithium-ion battery materials have focused on developing nanostructured materials for improved electrochemical performance [145]. Nanostructured anode materials like silicon nanowires and carbon nanomaterials derived from black carbon soot have shown promise for high-performance lithium-ion batteries. Selective deposition and stable encapsulation of lithium through heterogeneous seeded growth have also been explored as reported in [146],[147]. Additionally, the preparation and electrochemical performance of ultra-short carbon nanotubes and the bulk preparation of holey graphene via controlled catalytic oxidation have been investigated [148].

B. Composite Electrodes

Composite electrodes, particularly those combining graphene and carbon nanotubes, have been studied for high-performance energy storage. Hybrid graphene ribbon/carbon electrodes and chemical-free synthesized graphene-carbon nanotube hybrid materials have shown reversible lithium storage capabilities in lithium-ion batteries [148], [149]. A 3D porous carbon network with synchronously improved graphitization and surface area has been developed as a high-capacity anode material [150]. In addition, the use of lithium-ion layered oxide and atomic layer deposition has been employed as a strategy for surface modification of electrodes.

A study [151] showed that bi-layered coated electrodes with TiO₂/ Al₂O₃ demonstrated exceptional capacity retention of about 90.4% and a specific discharge capacity of 146mAh/g after 100 cycles. The work shows that coated electrode reduces voltage decay, lowers surface film resistance and improves the interfacial charge transfer which enhances battery stability.

C. High-Energy-Density Materials

Researchers have also focused on developing high-energy-density materials for lithium-ion batteries. Advances in multi-metallic alloy-based anodes for alkali-ion and alkali-metal batteries have been reported [168]. Silicon-based anodes, despite challenges, have shown effectiveness in materials synthesis and electrode preparation for improved energy density [97], [96]. Lithium-rich layered oxide cathodes with advanced carbon cloth used as current collectors have demonstrated enhanced electrochemical performance [151]. Advancements in nano-structured materials, composite electrodes, and high-energy-density materials are pushing the boundaries of LIB performance. These innovations hold immense promise for the future of portable electronics, electric vehicles, and large-scale energy storage. However, further research is needed to address remaining challenges like cost, safety, and long-term stability to fully realize the potential of these next-generation LIB materials.

VII. CONCLUSION

Lithium-ion batteries have become the dominant energy storage technology for portable electronics, electric vehicles, and grid-scale applications due to their high energy density, long cycle life, and low cost. However, further improvements in battery materials are needed to enable the widespread adoption of EVs and renewable energy. Promising new anode materials include silicon and tin alloys which can store much more lithium than graphite, enabling higher energy density. On the cathode side, layered lithium-nickel-manganese-cobalt oxides (NMC) and lithium-nickel-cobalt-aluminum oxides (NCA) have largely replaced lithium cobalt oxide (LCO) due to their higher energy density and lower cost. Emerging cathode materials like lithium-rich layered oxides and lithium-sulfur can potentially double energy density compared to current NMC/NCA cathodes. Solid-state electrolytes are also being intensely researched as a way to enable high-capacity lithium metal anodes and improve safety. The future of lithium-ion batteries lies in the development of advanced energy materials that address the limitations of current technologies. From high-capacity cathodes and anodes to safe and efficient electrolytes and separators, these materials hold the key to unlocking higher energy densities, faster charging, and improved safety. While significant challenges remain, ongoing research and innovation are paving the way for a new generation of LIBs that will power the sustainable energy systems of tomorrow. With continued advances in materials science and manufacturing, lithium-ion batteries will likely remain the dominant energy storage technology for the foreseeable future.

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