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Nanotechnology-Driven Innovations in Lithium-Ion Battery Anodes: Materials and Performance Insights

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Abstract

The development of high-performance anode materials is critical to advancing lithium-ion battery (LIB) technology for applications ranging from portable electronics to electric vehicles. This review emphasizes the advancements of nanotechnology in lithium-ion battery (LIB) electrode materials, with a primary focus on the anode materials, and provides a comprehensive overview of recent advancements in the carbon-based, silicon-based, tin-based, and metal-organic framework (MOF)-based anode materials. Graphite, the conventional anode material, is limited by its low specific capacity (372 mAh g^{1}); recent progress in carbon nanotubes (CNTs) and graphene-based composites has shown enhanced performance, with CNTs achieving capacities above 1100 mAh g^{1} and improved rate capabilities due to high conductivity and large surface areas. Silicon-based anodes offer a theoretical capacity of ~4200 mAh g^{1} but suffer from severe volume expansion; strategies such as nano-Si/carbon composites and core-shell architectures have significantly improved stability, achieving cycle lives over 1000 cycles with capacities exceeding 600 mAh g^{1}. Tin-based materials, including Sn and SnO_2 composites, show capacities around 750–1200 mAh g^{-1}, with enhanced stability through nanostructuring and carbon-based buffering matrices. MOF-derived anode materials have emerged as promising candidates due to their tunable porosity and high surface areas, supporting stable cycling and efficient lithium-ion transport. Collectively, these innovations present viable pathways to overcome the intrinsic limitations of traditional anode materials, offering improved electrochemical performance essential for next-generation LIB applications. In addition, the challenges of integrating these materials into practical applications, such as scalability and long-term stability, are critically analyzed. Finally, future prospects are outlined, focusing on enhancing energy density, improving safety features, reducing costs, and advancing sustainable production methods and recycling technologies to address the growing demand for green energy solutions.

Keywords: Lithium-ion battery; anode materials; battery performance; sustainable energy; advanced materials

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1. Introduction

The progress of renewable energy sources, including wind and solar power, is crucial for achieving the Sustainable Development Goals (SDGs) focused on reducing global reliance on fossil fuels and mitigating their environmental impact, particularly carbon dioxide emissions. Innovations in energy storage technology, such as lithium-ion batteries (LIBs), are essential for ensuring the reliable and long-term storage of electrical energy, which is vital for electric vehicles, portable devices, and energy storage systems [1-3]. LIBs offer several benefits over traditional battery technologies, including a longer cycle life, higher output voltage, lightweight design, and superior energy density [4]. Their high energy density makes LIBs an ideal choice for applications where space and weight constraints are critical, allowing significant power storage in a compact design. The minimal self-discharge rate of LIBs enables them to retain their charge for extended durations when not in use [5-7].

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The exceptional energy density, elevated electrochemical potential, and lightweight nature of lithium render LIBs highly advantageous. It was reported that the development of rechargeable LIBs in the 1970s by utilizing lithium metal as the anode due to its high energy density advantage [8].In 1990, Sony launched the first commercially viable LIB, including a graphite anode and a $LiCoO_2$ cathode [9, 10]. However, safety concerns initially limited their widespread use. Subsequent innovations, such as Y. Chiang's enhancement of thermal conductivity in 2002 and the adoption of nanophosphate cathodes in 2004, significantly advanced energy density, cycle life, and safety [11].

During charge and discharge cycles, LIBs enable the transfer of lithium ions between the positive and negative electrodes, allowing for efficient energy storage and release. Each critical component of LIB contributes uniquely to its functionality and performance. The cathode, typically made of lithium metal oxides or phosphates, determines the battery's voltage and energy density. The anode, often composed of graphite or advanced materials, enhances the battery's overall performance. The separator provides electrical insulation to prevent short circuits, while the electrolyte facilitates ion transport between electrodes [12, 13]. Current collectors enable efficient charging and discharging processes. These electrochemical interactions, as depicted in Fig.1, drive the overall energy storage and release mechanism within the battery cell.

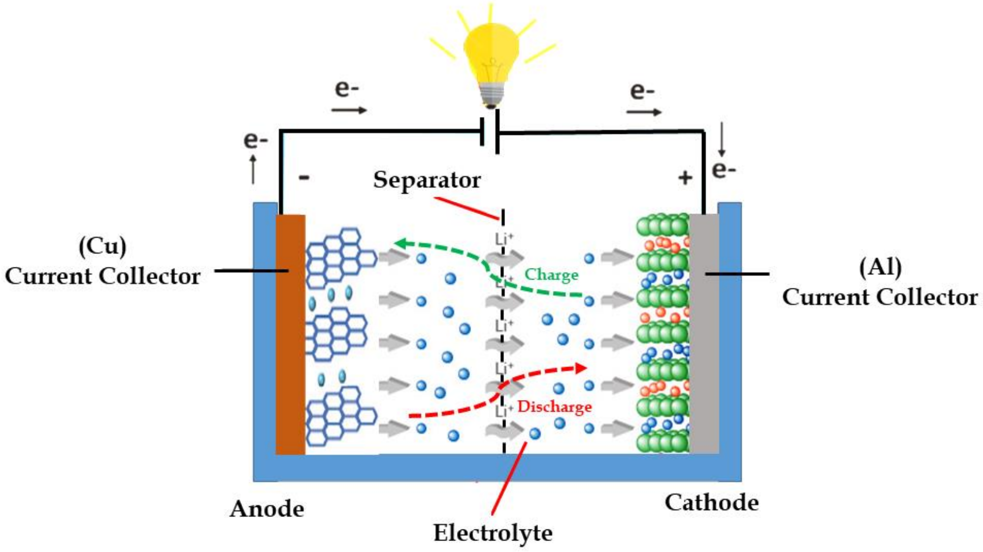

Fig.1. Schematic diagram of charging-discharging in LIB.

In Sony's commercial LIBs, lithium ions move when an electrical current is applied. These ions are stored in graphitized carbon (Li_xC_6), which serves as the anode storage medium, as they leave the cathode ($Li_{1-x}CoO_2$). During discharge, lithium ions are transferred back to the cathode, generating an electric current that powers external devices. At 3.0-4.2 V, $LiCoO_2$ electrodes have a practical capacity of roughly 140 mAh/g, constituting about 50% of the theoretical capacity of 273 mAh/g. The discrepancy is attributed to the instability and surface reactivity of the delithiated $Li_{1=x}CoO_2$ structure. The search for appropriate alternatives to $LiCoO_2$ as a cathode material has been extensively researched since 1991. This is attributable to its disadvantages, which encompass the high cost of cobalt and the risk of thermal runaway resulting from overcharging or short circuits. The fundamental objectives of material research and development are to improve the safety, durability, cycle life, and energy density of lithium-ion cells [14, 15].

To achieve optimal energy density and extended cycle life in LIBs, the materials employed as electrodes in electrochemical cells must exhibit stability. Recent advancements have greatly enhanced the safety, efficiency, and sustainability of these materials. Silicon-based anodes, known for their high capacity, have garnered significant interest, though challenges such as volumetric expansion persist. Research efforts also focus on improving stability and conductivity by exploring transition metal oxides and alloying materials. The growing need for efficient and high-performance energy storage systems is propelling these advancements [16]. This work shows recent progress in LIB anode materials, including their composition, performance improvements, and associated challenges. Key advancements, such as those in silicon-based anodes, highlight pathways to enhance energy density, cycle life, and safety. Additionally, the paper emphasizes the importance of emerging trends and sustainable solutions to meet future energy demands. By addressing these developments, we aim to support researchers and industries in advancing LIB technologies for diverse applications.

2. Role of Nanotechnology in LIB’s

Nanotechnology has profoundly influenced the advancement of LIBs, particularly using nanocomposites, which offer an innovative approach to enhancing battery performance [17]. By combining a matrix material with a dispersed nanoscale phase, nanocomposites improve the overall functionality of LIBs. Moreover, nanotechnology has been instrumental in the development of advanced LIB anode materials. The incorporation of nanostructured materials, nanoparticles, and nanocomposites has enabled the creation of materials with improved stability and capacity, significantly boosting battery performance. These innovations have contributed to the production of high-performance LIBs, which are now extensively utilized in various applications, including portable devices, electric vehicles, and grid energy storage systems [17]. A critical focus of nanotechnology research is minimizing the diffusion path length for lithium ions; hence, enhancing the performance and energy density of active materials. A promising approach involves the development of nanoscale energy storage materials such as nanostructured silicon, tin, or sulfur, which could significantly enhance the energy density of LIBs [18]. Nanotechnology also offers innovative solutions for improving the effectiveness of electrolytes in LIBs. For instance, nanoscale ceramic coatings or additives can stabilize the electrolyte medium, preventing undesirable reactions like the formation of solid-electrolyte interphase (SEI) layer and electrolyte degradation. These advancements enhance safety and extend battery life [19]. Furthermore, nanofiber-based separators are under development, featuring improved mechanical strength, controlled pore size, and high porosity. These separators enhance battery performance and safety by lowering internal resistance, improving thermal stability, and enhancing electrolyte wettability [20]. For optimal LIB functionality, the electrode-electrolyte interface must be stable. Nanotechnology enables protective coatings on electrode surfaces, such as solid-state electrolytes or ultra-thin polymer layers. These coatings stabilize the interface, reduce interfacial resistance, and prevent harmful reactions, leading to improved battery performance and extended cycle life [21].

2.1. Nanotechnology in anode materials

The instability and limited capacity of anode materials are major challenges in the development of LIBs, significantly affecting their overall performance. Nanotechnology has shown great promise in addressing these issues by enabling the creation of more durable and higher-capacity anode materials. Among the various approaches leveraging nanotechnology, nanostructured materials have attracted the most attention [11, 15]. These materials exhibit enhanced electrical and mechanical properties due to their nanoscale, symmetrical, and organized structures. Notable examples include carbon nanotubes and graphene, which are widely used in anode design. Their outstanding mechanical strength, large surface area, and excellent electrical conductivity make them ideal for enhancing LIB performance [14, 18].

One of the most promising approaches involves the engineering of core-shell nanostructures, in which an active material forms the core, encapsulated by a shell composed of carbon, metal oxides, or graphene. These designs offer a dual advantage: the shell accommodates the significant volume expansion of the core during lithiation, thereby preventing mechanical fracture, while also enhancing electrical conductivity and stabilizing the solid electrolyte interphase (SEI). For example, silicon nanoparticles coated with a conductive carbon shell have demonstrated remarkable cycling stability, with high reversible capacities retained over extended cycling, highlighting the efficacy of this architecture in buffering structural stress and suppressing SEI growth [22]. On the other hand, porous nanostructures have also garnered considerable attention due to their ability to alleviate mechanical strain and facilitate efficient lithium-ion transport. By introducing internal voids and a high surface area, these materials provide sufficient space to accommodate volume changes and enable rapid electrolyte infiltration. Mesoporous silicon-based anodes, for instance, have exhibited improved rate capabilities and long-term structural integrity, attributed to the mitigated stress concentrations and enhanced diffusion pathways within the porous network [23, 24]. Another widely applied nanostructuring strategy involves surface coating techniques, where nanoparticles are coated with thin layers of conductive or protective materials. These coatings, typically composed of carbon, metal oxides, or polymeric films, play a vital role in controlling surface reactions and improving electrode-electrolyte compatibility. The coated layers not only enhance electronic conductivity but also act as artificial SEI layers that prevent uncontrolled decomposition of the electrolyte. This leads to more uniform SEI formation, higher coulombic efficiency, and a significant extension of the battery’s lifespan. For instance, tin oxide nanoparticles coated with reduced graphene oxide (rGO) have demonstrated superior performance due to the synergistic effect of enhanced conductivity and SEI stabilization [25]. Consequently, Fig.2 shows how nanotechnology structures, such as core-shell, porous, and embedded configurations, significantly enhance the stability of electrode materials by reducing particle cracking and forming a stable SEI layer during cycling. Besides, Nanoparticles have a very high surface-to-volume ratio, which makes them perfect for improving the electrochemical performance and reactivity of LIB anodes. This makes the batteries more stable and increases their capacity. Investigations into anode materials have predominantly focused on silicon nanoparticles owing to their exceptional cycle stability and elevated capacity. The nanoparticles' volume increases when they are charged, which makes them more likely to break down mechanically and lose their capacity. To solve these issues, researchers are looking into new ways to make silicon nanoparticle-based anodes more stable and effective. These include hybrid materials, surface changes, and complex three-dimensional designs [7, 19].

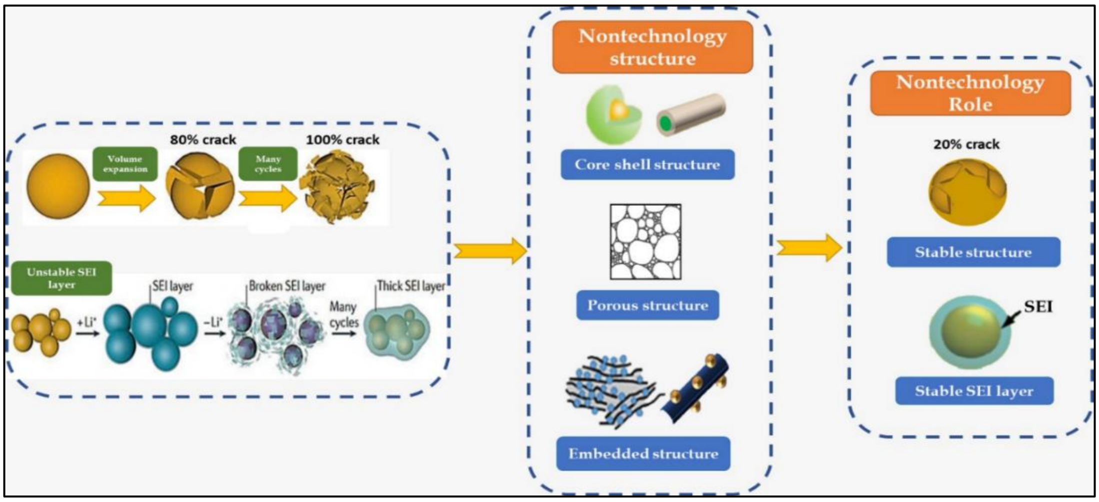

Fig.2. Illustration of the effect of using nanostructure technologies on the stability of electrode materials

Recent studies demonstrate that nanocomposite anode materials can markedly enhance the stability and capacity of LIBs. Clay-based nanocomposite anodes have attracted considerable interest from researchers for LIBs owing to their outstanding capacity and impressive cycling stability. The clay particles in the composite serve as a framework, while the matrix material offers substantial mechanical support and enhanced conductivity. This allows the composite to accommodate volume fluctuations caused by the insertion and removal of lithium-ion cells [26]. Despite the promising performance of nanoscale materials, particularly nanoparticles, their effectiveness in LIBs is constrained by several factors. Volume expansion and fracturing of nanoparticles during repeated lithium-ion insertion and removal cycles can adversely affect battery life and cyclability. The random walk of electrons and Li^+ ions through nanoparticulate layers can impede their movement, limiting efficient transport across the nanostructures. Furthermore, diffraction boundaries and vacancies in the nanoparticles contribute to reduced electrical conductivity and overall performance. The solid electrolyte interphase (SEI) film can form at the electrode-electrolyte interface as a byproduct of electrolyte decomposition and other processes, resulting from the interaction between the electrolyte and the nanoparticles' extensive surface areas [26]. During the first charging cycle, a critical formation process is induced because of electrolyte/anode material, electrolyte/additives decomposition, and migrated Li/binder complex interactions. Consequently, secondary interaction and copper dissolution are greatly reduced, which leads to a far-expanded lifetime. For using a nanostructured anode material, the electrolyte/electrode interface thermodynamic stability window is affected as the electrode's potential as well as chemical potential is shifted with dimension concerning the electrolyte LUMO bandgap [27, 28]. Moreover, High-surface-area nanoparticles dramatically accelerate undesirable side reactions that induce a much thicker heterogeneous SEI layer, which induces irreversible capacity loss [29]. Besides, high volumetric expansion materials like Si are showing re-formation of SEI layers during cycling, these processes consume lithium as well as form a penetrated network that greatly increases cell impedance [30].

3. Classification of Anode Materials

The development and application of various anode materials for LIBs have been influenced by various factors, typically categorized based on their chemical composition. Fig. 3 illustrates the various types of anodes used in LIBs based on their underlying mechanisms. The initial group of anodes comprises intercalation materials, including carbon-based compounds and lithium tin oxide. The second type comprises alloying anodes that integrate components such as silicon and tin. The third category consists of conversion anodes, predominantly made of transition metal oxides and sulfides. Carbon-derived materials, such as graphite and amorphous carbon, are highly favored. Despite possessing excellent electrical conductivity and lithium-ion storage capacities, these materials often exhibit insufficient cycle stability and a poor overall capacity [20, 21]. Metal-based anodes, including magnesium, aluminum, and lithium, boost both electrical conductivity and lithium-ion storage capacity. Their rapid volume expansion while charging may lead to mechanical deterioration and a reduction in capacity [9, 11, 31]. Semiconductor-based materials, such as silicon and tin, represent another promising category. While these materials can store large amounts of lithium, their significant expansion during charging can cause mechanical wear and a gradual loss of capacity. Composite materials provide a versatile alternative by combining multiple components to leverage the advantages of different materials, potentially overcoming the limitations of individual ones. For instance, incorporating composites that integrate a high-capacity nanoparticle phase with a conductive matrix can enhance both electrical conductivity and capacity [14, 32]. Another method of classifying anode materials is by their structural configuration, including bulk materials, thin films, and nanoparticles. Bulk materials are macroscopic solids, while thin films have thicknesses on the micron or nanometer scale. Nanoparticles, with their unique properties, offer further potential for advanced anode design [33].

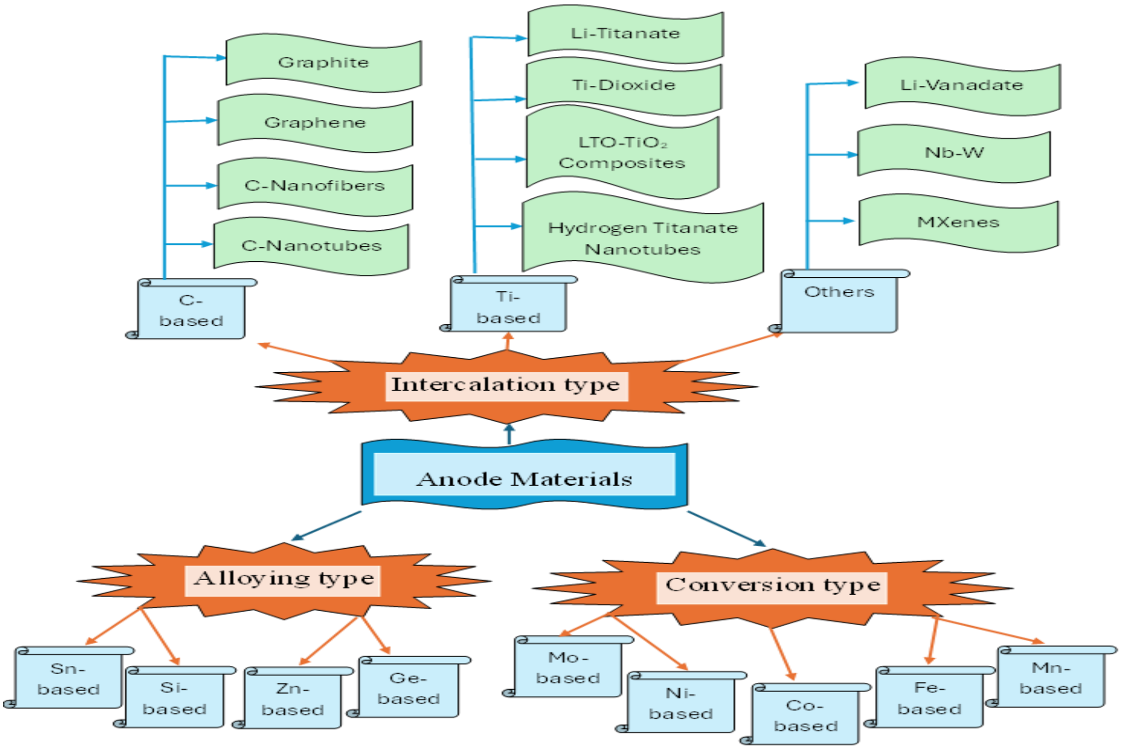

Fig. 3. Categories of anode materials used in LIBs.

3.1. Carbon-based anode materials

The adaptability, affordability, and relative simplicity of producing carbon-based materials for anodic reactions render them optimal for LIB anodes as in Eq. 1 [31]:

$$\alpha Li^{+} + \alpha e^{-} + \alpha C_6 \leftrightarrow \alpha LiC_6 \qquad (1)$$

The predominant ingredients consist of graphite carbon, often referred to as soft carbon. Graphite carbon has superior crystallinity; nonetheless, it possesses a low specific capacity of 372 mAh g^{-1} due to the slow intercalation of lithium ions. Nonetheless, the use of hybrid and electric vehicles may be restricted due to this limitation [20, 34] Conversely, hard carbon, or non-graphite carbon, possesses a disordered internal crystalline structure and exhibits stability; yet it faces challenges related to high reversibility and capacity degradation [35]. According to studies, particle size, additives, and high porosity are elements that contribute to its significant reversibility. Furthermore, research has shown that nanometer-scale particles can enhance specific capacity, reduce lithium-ion diffusion length, and augment structural stability through the application of low-dimensional structures. The fabrication and modification of carbon materials to optimize their properties have consistently garnered significant interest [15, 19]. Due to their large surface area, excellent electrical conductivity, and high mechanical strength, carbon nanotubes (CNTs) are a very good anode material for LIBs. These cylindrical nanostructures, measuring 1–2 nanometers in diameter and stretching several micrometers in length, may display metallic or semiconducting characteristics [31, 36]. Carbon nanotubes are categorized as single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs) based on their wall thickness. Due to their extensive surface area, carbon nanotubes are optimal for LIB applications, as they effectively absorb a significant quantity of lithium ions, hence enhancing the anode's specific capacity [32, 33]. Additionally, CNTs improve battery rate performance by significantly shortening the lithium-ion diffusion path. Their outstanding electrical conductivity and mechanical robustness also contribute to better stability and safety of LIBs [37, 38].

Studies have demonstrated that CNTs can achieve a storage capacity exceeding 1116 mAh g^{-1}, inclusive of irreversible lithium storage. Lithium ions can adhere to both the internal and external surfaces of CNTs. Research has revealed that while some lithium ions may penetrate the nanotubes through fissures or open ends, this does not affect the battery's reversible capacity. The interlayer spacing in MWCNTs, approximately 0.34 nm, can accommodate lithium ions. The curved morphology of CNT walls can augment storage capacity by promoting lithium condensation. Composite materials using CNTs significantly improve the performance of LIB anodes [38]. Nanocomposites composed of clay have garnered extensive research attention owing to their superior capacity and exceptional cycling stability. The matrix material provides robust mechanical support and enhanced conductivity, and the clay particles function as a scaffold to accommodate the volume fluctuations that arise during lithium-ion insertion and extraction. Challenges continue to exist despite the exceptional characteristics of nanoscale materials like carbon nanotubes. The cyclability and longevity of batteries may be adversely affected by the volumetric expansion and fracturing that transpires during the repeated insertion and extraction of Li^+ ions. Decreased efficiency may arise from the stochastic movements of electrons and Li^+ ions within nanoparticulate layers, which can hinder their unrestricted mobility. Defects and vacancies may adversely affect the overall electrical conductivity and performance of nanoparticles.

Despite their potential, several challenges must be overcome before CNT-based anodes can be considered economically viable for widespread application. One key issue is the lack of advanced, cost-effective methods for producing carbon nanotubes (CNTs) with precise and uniform structures, which directly impact their electrical properties and anode performance. Another major concern is the irreversible lithium-ion capacity of CNT-based anodes, where some lithium ions are consumed rather than retained, reducing the overall capacity. Additionally, significant voltage fluctuations during discharge render CNT anodes unsuitable for electronic systems that require stable voltage output [39]. To address these challenges, advanced research efforts are focusing on developing innovative synthesis processes and optimized architectures for CNT-based anodes. Promising approaches include the design of core/shell composite anodes combining CNTs with other materials and the decoration of CNTs with metal nanoparticles to enhance performance. The structure and morphology of CNTs are being examined by utilizing advanced characterization techniques such as field emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM). This research elucidates the influence of CNTs on anode performance [34, 40]. By resolving these challenges, it is aspired to eventually implement CNT-based anodes in LIBs effectively and pragmatically.

The LIB anodes often incorporate hard carbon, a non-graphitic form of carbon, as a key material [33, 41, 42]. This material is highly regarded for its exceptional stability, which is attributed to its disordered internal crystalline structure. However, this same structure poses challenges, such as limited reversibility and capacity degradation. Despite these drawbacks, hard carbon is extensively studied as a potential anode material due to its notable lithium storage capabilities. One of the primary advantages of hard carbon is its substantial storage capacity. The disordered internal crystallites provide a large surface area for lithium-ion binding, enabling a specific capacity of up to 1000 mAh g^{-1}, which surpasses that of traditional materials like graphite [39]. Additionally, its inherent stability is a significant benefit. Unlike graphite, which may become unstable under high temperatures or voltages, hard carbon remains stable across a wide range of conditions. Therefore, improved stability makes it an excellent candidate for high-performance LIBs, especially for demanding applications like electric vehicles [43].

However, there are some issues associated with utilizing hard carbon as an anode. The significant reversibility is a substantial challenge as it may lead to a decrease in capacity over time. Lithium ions might diffuse from the hard carbon during charging and discharging, explaining this phenomenon. Researchers have been endeavoring to address this issue by discovering enhanced methods to modify the characteristics of hard carbon and refine its structure [43]. Furthermore, modifying the structure of hard carbon anode materials presents a potential solution to address their reversibility challenges. Recent studies demonstrate that transforming hard carbon into a nanostructured form can substantially reduce its diffusion length, thereby enhancing its performance. This can enhance both the material's reversibility and specific capacity [35]. The performance of anodes and their structural stability can be improved through the incorporation of additives such as metal nanoparticles. Another potential anode material that scientists have been looking into is high-porosity hard carbon. Anode reversibility and storage capacity can be enhanced using high-porosity materials due to their higher surface area and ability to accommodate more lithium ions [44]. Comprehensive research on graphene-based anode materials and the integration of lithium ions into carbon-based anodes in LIBs has resulted in significant advancements in our understanding of this process. To create more stable anode materials that have a greater capacity to store energy, and last longer, this knowledge is essential [35, 45, 46].

Graphene, a two-dimensional (2D) nanomaterial, has attracted significant attention owing to its distinctive characteristics and structure, which may be advantageous for LIBs. The material exhibits a thermal conductivity of 3000 W/mK and a substantial surface area of 2600 m^2/g [47-49]. The configuration consists of a monolayer of hexagonally arranged carbon atoms. The configuration of two-dimensional graphene offers numerous advantages, including exceptional mechanical strength, elevated charge carrier mobility (about 200,000 cm^{-1} s^{-1}), and remarkable electrical conductivity [10, 46]. The enormous surface area of graphene facilitates more efficient charge transfer between the electrolyte and electrode, hence enhancing battery performance [50]. Recent studies have progressively investigated nitrogen-doped graphene as a viable anode material for LIBs. When nitrogen atoms are added to the graphene, the defect density goes up. This increases the number of active sites for lithium storage, which makes the electrochemical process more efficient. Because nitrogen has an atomic size like carbon and a higher electronegativity, it makes it easier for lithium ions to interact with carbon materials that have nitrogen added to them. A recent study shows that adding heteroatoms, especially nitrogen, to graphene makes it much better at storing lithium ions [51]. A novel generation of graphene-based composites has been created for LIB anodes [52]. These composites, which are made by mixing graphene with polymers and parts like silicon, tin, lithium cobalt oxide, and titanium dioxide, are much better at storing lithium and cycling than pure graphene [10, 11, 15].

Furthermore, applications necessitating substantial power and capacity significantly advantage from graphene's two-dimensional structure, facilitating swift Li+ ion mobility. Due to its two-dimensional structure and additional advantages, graphene demonstrates potential as a material for next-generation LIBs. Utilizing it as a composite material in the electrode enhances the battery's capacity and enables greater lithium-ion storage, hence extending battery life [51]. Graphene's remarkable features, such as superconductivity, high electron mobility, and the quantum Hall effect, enable a wide variety of applications. Additionally, incorporating heteroatoms such as nitrogen into the graphene structure significantly enhances its electrochemical performance [51].

Despite the superior advantages of graphene, there are several limitations to using graphene as an anode material. The major drawback of using graphene in LIBs lies in its limited capacity to retain lithium ions. The propensity for graphene layers to restack and the restriction of lithium ions to intercalate solely within the basal planes of graphene result in a constrained theoretical capacity for lithium storage, despite graphene's elevated specific surface area. A further disadvantage is that graphene exhibits a sluggish rate of lithium insertion and extraction. The difficulty in transporting lithium ions arises from the 2D structure of graphene that they must navigate to access the active spots [10, 14]. Consequently, LIBs utilizing graphene as an anode material may exhibit extended charging and discharging durations [39, 47, 51]. Graphene, a two-dimensional (2D) nanostructured material, has gained considerable attention for LIB applications due to its distinctive structure and properties. Fig. 4 displays scanning electron microscope (SEM) and transmission electron microscope (TEM) images of reduced graphene oxide (RGO).

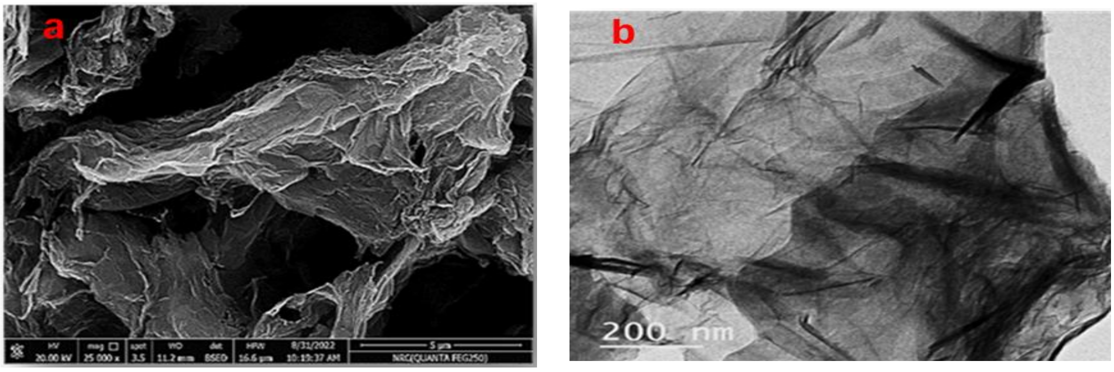

Fig. 4. a) SEM micrographs of (2D-RGO), b) TEM micrographs of (2D-RGO).

3.2. Silicon-based anode materials

Silicon possesses a superior theoretical specific capacity compared to graphite, rendering it a potential substitute for graphite as an anode material in LIBs. Silicon offers approximately tenfold the capacity of graphite, exhibiting 4200 mAh/g in contrast to graphite's 372 mAh/g. Anode materials for LIBs use silicon's elevated capacity, hence enhancing the energy density of the batteries. Enhancing silicon anode performance necessitates an understanding of the electrochemical lithiation mechanism. The reaction process is elucidated using Eqs 2 and 3 for discharging and Eq. 4 for charging[10, 11].

$$\text{Crystalline (Si)} + \alpha Li^{+} + \alpha e^{-} \rightarrow Li_{\alpha}Si\ \text{(Amorphous)} + (3.75-\alpha)\ Li^{+} + (3.75-\alpha)\ e^{-} \quad (2)$$

$$\text{Si (crystalline)} + \alpha Li^{+} + \alpha e^{-} \rightarrow Li_{15}Si_{4}\ \text{(crystalline)} \quad (3)$$

$$Li_{15}Si_{4}\ \text{(crystalline)} \rightarrow \text{Si (amorphous)} + yLi^{+} + ye^{-} + Li_{15}Si_{4}\ \text{(residual)} \quad (4)$$

However, the use of Si in LIBs is not straightforward due to its tendency to swell during cycling, which leads to mechanical failure of the battery. The swelling of Si during charging is caused by the large volume change that occurs when lithium ions are intercalated into the Si structure. To overcome this issue, various Si-based materials have been developed, including nanoscale Si, silicon nanowires, and silicon/carbon composites [53].

Recent research has extensively explored the utilization of nSi in LIBs, leading to the development of various techniques to enhance its electrochemical efficacy [32]. A technique within this category entails the encapsulation of nSi particles with conductive and protective substances, such as carbon nanotubes or nitrogen-doped graphene. Altering its surface can enhance the anode's stability, increase its electrical conductivity, and reduce the likelihood of mechanical failure during cycling. Incorporating carbon materials into the anode can enhance its electrochemical performance and mitigate volume fluctuations. The incorporation of nSi and carbon into the anode enhances its mechanical stability and cycling performance, hence augmenting the battery's energy density [11, 14]. In addition to the above-described approaches, hierarchical architecture and doping with metals and non-metals have also been developed to enhance the efficiency of nSi-based anodes. To improve its electrochemical performance, nSi can undergo modifications to its electronic structure through doping with metals or non-metals. To improve the anode's stability and cycling performance, hierarchical topologies such as core-shell architectures and three-dimensional nanostructures may be utilized [9, 10].

Before nSi realizes its full potential in LIBs, it is essential to resolve numerous challenges. The inadequate electrical conductivity significantly diminishes the battery's performance. Troublesome issues include broken particles, delamination, unstable electrical contact, poor electron transport, and the growth and creation of SEI layers [32]. Large changes in the anode's volume cause these problems. The anode utilizes silicon. Enhancing the efficacy of nSi-based anodes necessitates further research and development to address these issues. To improve electrochemical performance, it is essential to develop scalable and cost-effective ways of producing nSi particles. This entails enhancing surface modifications and hierarchical structures [7, 43].Bai et al. evaluated the performance of an advanced composite material incorporating nanostructured silicon as an anode for LIBs. The composition consisted of silicon nanoparticles and functionalized carbon nanotubes embedded within a polyaniline (PANI) matrix. Their study demonstrated that the three-dimensional PANI conductive framework significantly enhanced cycling stability and Li-ion diffusion kinetics by remaining intact during the low-temperature sintering of the double-protected silicon nanoparticles. The Si@C/PANI-CNT composite had a very low capacity loss of only 0.084% per cycle after 500 cycles and a very high discharge capacity of 879 mAh g^{-1} at a current density of 0.5 A g^{-1}. The strong hierarchical three-dimensional structure allowed for great long-term performance, keeping a specific capacity of over 605 mAh g^{-1} for more than 1,000 cycles, even when the current density was high at 1 A g^{-1}[54].

Pinilla et al. [55] investigated hybrid electrodes that combine two-dimensional and one-dimensional silicon nanostructures, revealing notable stability and capacity performance. The electrodes, produced through conventional methods, maintained their functionality at 2 A g^{-1} over 500 cycles, achieving capacities up to 1200 mAh g^{-1}. Electrode hybrids are fabricated through conventional techniques such as doctor blade coating (tape casting) for large-scale thin-film production, chemical vapor deposition (CVD) for accurate thin-film deposition of materials such as metal oxides or carbon nanotubes [56], and more straightforward methods like drop casting for small-scale research [57].

The 0D nanostructures within these hybrid electrodes facilitated strain relaxation, while the 1D nanomaterials strengthened the conductive matrix and improved structural cohesiveness. Meanwhile, Zhou et al. [58] indicated that anodes composed of templated carbon-bridged orientated graphene, covered with silicon nanoparticles, exhibited exceptional lithium storage capacity. Remarkable cyclic stability was achieved, exhibiting a degradation of 0.025% per cycle over 200 cycles, alongside a substantial volumetric capacity of 1807 mAh cm^{-3}, a rate capability of 900 mAh g^{-1}, and an elevated gravimetric capacity of 1390 mAh g^{-1} at 2 A g^{-1}.

3.3. Tin based materials

Considering the previous studies, tin (Sn) exhibits low toxicity, substantial theoretical capacity, and affordability, making it an attractive candidate for the anode material in LIBs [32, 59]. Accordingly, tin can significantly enhance the capacity of LIBs due to its high lithium storage potential. Eq. 5 illustrates the reversible reaction between tin and lithium, leading to a substantial theoretical specific capacity of 993.4 mAh/g. Nonetheless, tin's mechanical instability and inadequate conductivity render it impractical for application in LIBs during charging and discharging cycles [10, 60].

$$Sn + \alpha Li^{+} + \alpha e^{-} \leftrightarrow 4Li_{\alpha}Sn \qquad (5)$$

A comprehensive investigation into tin nano-structure intercalations with advanced materials has resulted in the creation of tin-based products that demonstrate enhanced efficiency in specific contexts. Thus, Sn nanoparticles, tin oxides, tin sulphides, and tin-carbon composites are the predominant tin-based materials employed in LIBs [50, 60, 61]. The efficiency of tin anodes can be improved by using tin nanoparticles, which exhibit a substantial surface area and remarkable conductivity. Research has shown that tin nanoparticle anodes, which mitigate volumetric expansion, provide superior performance and stability throughout charge/discharge cycles. Zhou et al. [62] employed MnOx nanowires as removable templates to develop an innovative method for encapsulating Sn nanoparticles within amorphous carbon nanotubes (CNTs). This Sn@aCNT hybrid material is ideal for LIB anodes due to its uniformly distributed Sn nanoparticles and resilient aCNT network structure. Remarkable high-rate performance is exhibited by its specific capacity of 573 mAh g^{-1} after 500 cycles at a current density of 1.0 A g^{-1}, and a significant specific capacity of 749 mAh g−1 after 100 cycles at a current density of 0.2 A g^{-1}. Porous carbon nanofibers embedded with Sn nanoparticles (Sn-PCNF) were synthesized by Shen et al. [63] by carbonization and a scalable electrospinning technique. At a current density of 0.8 A g^{-1} after 200 cycles, the electrode material exhibited exceptional electrochemical performance, achieving a capacity of 774 mAh g^{-1}.

On the other hand, the composite-based carbon structure can address tin's limited mechanical stability, thereby improving cycle performance and capacity retention. Based on these considerations, Lian et al. [64] developed a three-dimensional carbon network electrode material, featuring a combination of porous nanoscale Sn@C and graphene. The incorporation of small Sn particles serves to delay particle pulverization and minimize overall strain. The porous architecture enables the gradual release of lithium during volume fluctuations, while the carbon layer acts as a protective barrier, preventing the aggregation and detachment of Sn particles. The 3D carbon network's structure of buffering and preservation of electrode conductivity results in a sustained reversible specific capacity of 600 mA h g^{-1} and exceptional cyclability. This approach proves to be effective for other high-capacity electrode materials that experience substantial volume changes during charge-discharge cycles [46, 65]. Another type of tin-based substance included in LIBs is tin oxide or SnO_2. This material undergoes anodic reactions with lithium, as illustrated in Eqs. 6 and 7. Due to their ability to improve the capacity and stability of tin anodes, tin oxides exhibit a significant theoretical capacity for lithium-ion storage. Tin oxides have had limited application in lithium-ion batteries due to their mechanical instability and inadequate conductivity [46, 65].

Consequently, researchers have dedicated extensive efforts to developing composites using graphene and other materials to improve the performance of tin oxide anodes. You et al. showed how to make carbon-coated two-dimensional porous C@SnO_2-rGO-SnO_2 nanosheets that can improve the performance of LIBs. At a current density of 200 mA g^{-1}, the C@SnO2-rGO-SnO_2 electrode exhibited remarkable reversibility, achieving a capacity of 1211 mAh g^{-1} after 300 cycles addressing the Eqs. 6 and 7. Remarkable rate performance was exhibited with a capacity of 545 mAh g^{-1} at 5 A g^{-1} and 315 mAh g^{-1} at 10 A g^{-1}. Furthermore, it demonstrated exceptional stability over extended cycles, achieving capacities of 703 mAh g^{-1} after 1200 cycles at 1 A g^{-1} and 525 mAh g^{-1} after 1200 cycles at 2 A g^{-1}[66].

$$SnO_2 + 4Li^+ + 4e^- \rightarrow Sn + 2Li_2O \qquad (6)$$

$$Sn + \alpha Li^+ + \alpha e^- \rightarrow Li_\alpha Sn (0 \leq \alpha \leq 4.4) \qquad (7)$$

Another tin-based material explored for LIBs is tin sulfide, particularly SnS_2 as in Eqs. 8 and 9. Anode materials for LIBs comprising tin sulphides exhibit potential owing to their superior conductivity and elevated theoretical capacity for lithium-ion storage [67]. Tin sulphides possess potential use in LIBs; nevertheless, their instability during charge and discharge cycles hinders widespread utilization. Moreover, it is essential to enhance the poor electrical conductivity and overall volume alterations of tin sulphides; thus, a range of electrochemical procedures has been proposed [46]:

$$SnS_2 + 4Li + 4e^- \rightarrow Sn + 2Li_2S \qquad (8)$$

$$Sn + \alpha Li^+ + \alpha e^- \leftrightarrow Li_\alpha Sn (0 \leq \alpha \leq 4.4) \qquad (9)$$

To address this issue, extensive work has investigated the potential of utilizing graphene and other materials in tin sulphide composites to enhance the stability of the anodes [40]. It was reported that a one-step hydrothermal method to synthesize biochars derived from sugarcane and SnS_2 nanosheet arrays in a hierarchical SnS_2/B composite. The SnS_2/B-9 combination exhibited exceptional crystallinity and stability, demonstrating an initial discharge specific capacity of 1107.4 mAh g^{-1} and sustaining 369.1 mAh g^{-1} after 50 cycles at 100 mA g^{-1}.

3.4. Metal-Organic Frameworks (MOF)

Metal-organic frameworks (MOFs) have a unique structure made up of metal ions and organic ligands that make charge transport more efficient. Their tunable pore size and high specific surface area make them excellent candidates for negative electrodes in LIBs [68, 69]. Because MOFs are porous, they can easily adapt to the changes in volume that happen when lithium-ion is added and taken out, as well as during charge and discharge cycles. This makes the battery more stable and effective. Altering the organic ligands in a battery can enhance its electrochemical performance by augmenting lithium-ion storage capacity and modifying the operating voltage [70]. To maximize the benefits of combining organic ligands with lithium ions, it is imperative to design MOF structures that possess a high surface area, significant porosity, and appropriate orientation, while also maintaining stability throughout the battery cycling process [33]. The synthesis of MOF-derived nanomaterials for application as anodes in lithium batteries typically commences with the self-assembly of MOF precursors into a protective template, which is then converted into the functional nanomaterial. Anode materials for lithium batteries frequently utilize metal-organic frameworks (MOFs) from the MOF, zeolitic imidazolate framework (ZIF), and metal-organic framework (MIL) families [71]. The anodic reaction involving lithium in LIBs and different metal-organic frameworks can vary in structure and chemical composition. Investigations into the anodic reactions of MOF-177 have concentrated on its prospective application as an electrode material in LIBs, as existed in Eqs. 10, 11, and 12[72].

$$Zn_4O(BTB)_2{\cdot}(DEF)_m(H2O)n + e + Li^+ \rightarrow Zn + Li_2O \qquad (10)$$

$$DEF + H_2O + e + Li^+ \rightarrow Li_2(DEF) + LiOH \qquad (11)$$

$$Zn + Li^+ + e \leftrightarrow LiZn \qquad (12)$$

Various methods are available for synthesizing MOF templates, including surface growth, mixed assembly, controlled etching, and out-diffusion. Studies have shown that incorporating multi-walled carbon nanotubes (MWCNTs) into zinc oxide-infused ferrites (ZIFs) before nucleation enhances battery performance by forming a porous network structure that strengthens the anode's integrity. To fully exploit the promise of MOFs as anode materials, we must first surmount several challenges. A critical issue is their limited electronic conductivity, which can result in lower power density and slow charge/discharge rates [73]. Researchers have sought to resolve this issue by augmenting the conductivity of MOFs via the use of conductive elements such as graphene or carbon nanotubes. It is crucial to ensure that the porous architecture and lithium-ion storage and release properties of MOFs remain unaltered by the inclusion of supplementary conductive agents [70]. The fabrication of MOFs for LIB anodes is fraught with challenges. Current methods for synthesizing metal-organic frameworks (MOFs) are often ineffective for large-scale production because of their elevated temperature requirements and protracted synthesis durations. The scalability of MOF synthesis is complex due to the influence of several synthesis parameters on the final product, such as reaction temperature, time, and precursor concentration [74].

Due to their elevated specific surface area (1,000 to 10,000 m²/g), precise pore size, customizable structure, and great affinity for guest molecules, metal-organic frameworks (MOFs) have been thoroughly investigated for prospective use in LIBs [7, 63]. Fig. 5 presents SEM and TEM images of Zif-67/RGO, demonstrating that the crystals possess a dodecahedral morphology characterized by distinct, uniform, and sharp edges. The distinctive structure of Zif-67, when integrated with reduced graphene oxide, inhibits the restacking of adjacent RGO nanosheets, rendering it an optimal composite material. In the porous active material, the homogenous distributions resulted in increased surface area, improved charge storage, and simple ion transport [75].

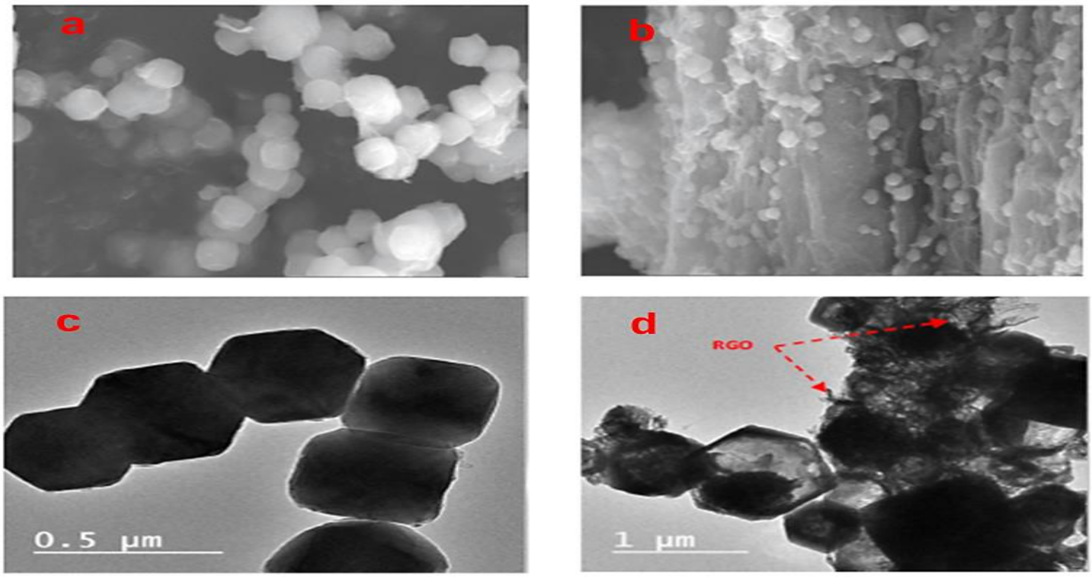

Fig. 5. FESEM images of (a) ZIF-67, (b) ZIF-67/RGO, (c) HRTEM images of RGO, (d) HRTEM images of Zif-67/RGO [75].

3.5. Transition metal oxides (TMOs)

Transition metal oxides (TMOs) are being actively explored as electrode materials for the anodes of lithium-ion batteries (LIBs) due to their unique properties, such as high gravimetric potential, abundance, high specific capacity, and potential to enhance battery performance [76]. Many TMOs can store lithium ions through intercalation lithium storage and conversion reaction lithium storage, as illustrated in Eqs. 13 and 14:

$$MO_x + yLi^+ + ye^- \leftrightarrow Li_yMO_x \quad \text{(Intercalation lithium storage)} \qquad (13)$$

$$MO_x + 2xLi^+ + 2xe^- \leftrightarrow M + xLi_2O \quad \text{(Conversion reaction lithium storage)} \qquad (14)$$

TMOs include Fe_2O_3, Co_3O_4, MnO, V_2O_5, and TiO_2. Some TMOs are derived from abundant and inexpensive resources, making them potentially cost-effective for large battery production. Compared to some other anode materials like silicon, certain TMOs can offer better safety characteristics. However, TMOs suffer limitations in their utilization, such as limited inherent electrical conductivity, which impedes electron transport and rate performance. Additionally, substantial volume expansion and contraction during lithium insertion and extraction might result in particle pulverization, electrode degradation, and capacity loss. To overcome the challenge facing the limitation of TMOs there are some modifications added to the preparation methods. Synthesizing TMOs with nanostructures (nanoparticles, nanowires, nanotubes, porous structures) can shorten lithium and electron diffusion pathways, increase surface area for electrochemical reactions, and better accommodate volume changes [77]. Combining TMOs with carbonaceous materials (graphene, carbon nanotubes, amorphous carbon) enhances the overall electrical conductivity of the electrode and can provide a buffering matrix to alleviate strain from volume expansion [78]. Carbon coatings can also prevent direct contact between TMOs and the electrolyte, improving stability. Furthermore, introducing foreign elements into the TMO lattice can modify its electronic and ionic conductivity [79].

3.6. Conductive polymers (CPs)

Conductive polymers (CPs) are being explored as anode materials for lithium-ion batteries (LIBs) due to their unique properties, offering potential advantages such as flexibility, lightweight nature, redox activity, tunable properties, and ease of processing [80]. Lithium-ion batteries commonly use conducting polymers including polyaniline (PANI), polypyrrole, and polythiophene (PT), as well as derivatives. These polymers are chosen due to extensive study, commercial availability, and simplicity of synthesis. Furthermore, conducting polymers are excellent for hybrid composites in lithium-ion batteries due to their significant electrical conductivity, conducting nature, and coulombic efficiency. The conductive nature of polymers arises from the presence of conjugated double bonds along their backbone. This unique structural feature allows for the delocalization of electrons, enabling them to move more freely throughout the polymer chain, which is essential for electrical conductivity. Despite the many advantages of polymers, there are certain limitations to their use. While the polymer electrode material fails to dissolve in the electrolyte during cycling, the polymer's insulative makes great cycling stability and rate capability challenging to obtain [81]. To overcome the insulativity of polymers, the primary way is through doping, which introduces mobile charge carriers into their conjugated π systems. Additionally, strategies like self-doping, and optimizing polymer design for lower band gaps and higher order. Moreover, forming conductive composites by introducing high-conductive materials like RGO and MWCNT are also crucial for enhancing and tailoring the electrical conductivity of these fascinating materials [82]. Germanium (Ge) anodes in lithium-ion batteries (LIBs) offer high theoretical capacity due to their superior electrochemical performance and high energy density. However, challenges like significant volume expansion during cycling limit their practical application. Nanotechnology-driven innovations, such as the incorporation of Ge nanoparticles or nanostructures, are being explored to enhance their stability and cycling performance in LIBs [83-86]. For further clarification of the recent review of the anode materials summary lists in Fig.6 and Table 1 emphasize the characteristics and performance of some common anode materials, including their type, capacity, and capacity retention.

Table 1. Common anode materials used in LIBs.

Anode Types	**Capacity (mAh g^{-1})**	**Capacity Retention %**	**References**
Li	3860	23.6-94.8 %	[31, 70, 72]
Graphite	≥ 372	64-91 %	[73, 87]
Hard Carbon (HC)	214-723	69.4-80%	[33, 41]
CNTs	160-1000	NA	[45, 47, 88, 89]
Graphene	404-1279	80- 98%	[45, 75]
Silicon	≥ 4825	42-95 %	[43, 90]
Tin based materials	441-1689	62.5-95.4 %	[46, 65, 68]
Germanium based materials	579-1385	55-82%	[83-86]
Metal, Transition metal oxides	161-2000	57-100 %	[9, 10, 91]
Metals	385-3350	NA	[11, 92]
Transition-metal compounds (Sulphides, phosphides, nitrides)	340-1800	84-98 %	[26]
MOF based materials	102-2,037	40-100 %	[63, 66, 93, 94, 95]

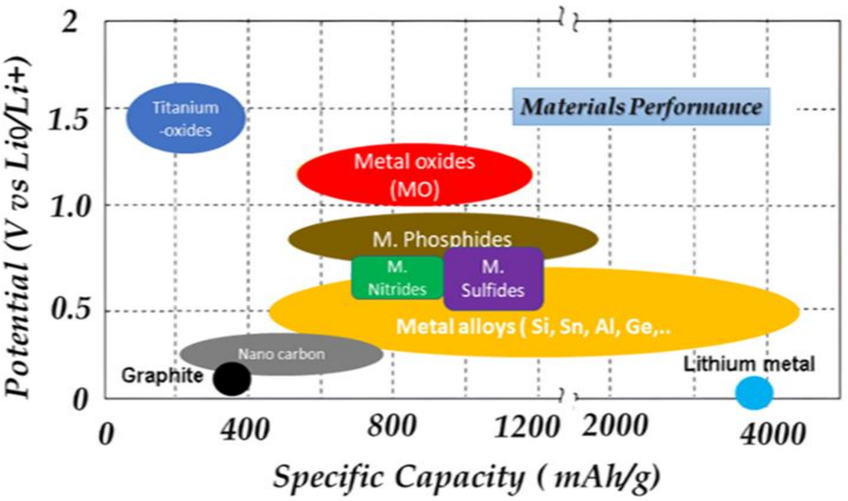

Fig. 6. Demonstration of the electrochemical performance of different anode materials.

4. Environmental impact of LIB anode materials

The environmental impact of LIB anode materials arises primarily from resource extraction, processing, and disposal. Graphite, the most used anode material, has significant environmental drawbacks, whether sourced from natural mining or synthetic production. Natural graphite mining leads to deforestation, habitat destruction, and high water consumption, while synthetic graphite involves energy-intensive processes that contribute to greenhouse gas emissions [96, 97]. Additionally, the refining process uses hazardous chemicals like hydrofluoric acid, which can contaminate water sources if improperly managed. With the growing demand for LIBs, concerns over the sustainability of graphite production have prompted research into alternative materials like silicon, and transition metal oxides. However, emerging nanostructured anode materials also pose environmental challenges; silicon-based anodes require extensive purification and high-temperature synthesis, increasing energy use and carbon emissions, while transition metal oxides, such as cobalt and manganese, involve mining that contributes to soil degradation, toxic waste, and heavy metal contamination [98, 99]. These materials also raise ethical and environmental concerns related to supply chain practices, particularly in regions with weak mining regulations. Furthermore, the nanoparticle nature of these anodes introduces potential toxicity and bioaccumulation risks, highlighting the need for further research on their long-term environmental impact. The end-of-life management of LIB anodes remains critical, as improper disposal leads to contamination and resource waste. Current recycling methods, such as pyrometallurgical and hydrometallurgical processes, are inefficient and generate secondary pollutants [100]. Accordingly, the schematic diagram depicted in Fig. 7 illustrates the sources of pollution of LIBs and their environmental impact. To address these challenges, researchers are exploring eco-friendly recycling methods, including direct recycling and bioleaching, and the development of biodegradable or more sustainable anode materials, such as biomass-derived carbon or metal-organic frameworks, which may reduce LIB-related environmental burdens [101].

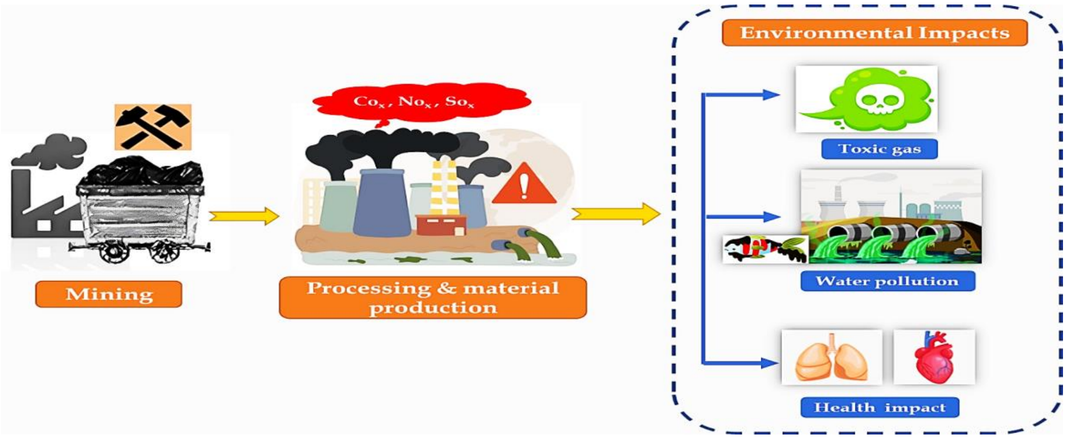

Fig. 7. Schematic diagram of environmental implications LIB anode materials

5. Marketing of Anode Materials for LIBs

The growing demand for high-performance energy storage in electric vehicles (EVs), portable devices, and grid storage has driven the rapid expansion of the anode materials market for LIBs. Graphite remains the dominant anode material due to its stability and cost-effectiveness, but the pursuit of higher energy densities and faster charging has driven research into advanced nanostructured materials like silicon-based anodes, transition metal oxides, and 2D materials. The commercialization of these materials depends on enhancing cycle life, mitigating volume expansion, and maintaining high efficiency while ensuring scalability. Silicon anodes, with ten times the theoretical capacity of graphite, have attracted significant investment from companies like Tesla and Panasonic. Advances in nanotechnology, such as carbon coatings and nanostructuring, are addressing challenges like silicon's volume expansion. Alternative materials, like metal sulfides, are being explored for niche applications requiring fast charging and safety. The selection of carbon sources, process management, the development of composites with high-capacity materials, and coating are all focal points in the research of carbon-based anodes. Graphite, possessing over 95% of the market share, is often regarded as the optimal material for lithium battery anodes. A trend is emerging to substitute graphite anodes with silicon-based and metallic lithium anodes, as graphite anodes near their theoretical capacity limit. Graphite anodes will persist in dominating the market for the foreseeable future due to their technological advantages, competitive pricing, and robust supporting industries [102].

In 2023, the global battery anode materials market was valued at approximately USD 2.06 billion and is projected to expand at a compound annual growth rate (CAGR) of 8.9%, reaching an estimated USD 4.3 billion by 2030. This growth is primarily attributed to the escalating adoption of EVs and the increasing need for efficient energy storage solutions. The silicon-based anode market is witnessing even more rapid expansion [according to the report: Battery Anode Materials Market Size, Share & Trends Analysis Report by Material (Lithium, Silicon, Graphite), By Application (Consumer Electronics, Automotive, Industrial, Telecommunication), By Region, And Segment Forecasts, 2024 – 2030). Valued at USD 421.6 million in 2023, it is anticipated to reach USD 4.46 billion by 2030, reflecting a robust CAGR of 40.1%. Projections indicate that by 2036, the silicon-based anode market could generate revenues up to USD 137 billion, underscoring the material's potential to replace graphite in LIBs. On the other hand, Graphite continues to hold a dominant position in the LIB anode market, accounting for over 95% of the market share. This prevalence is due to its established manufacturing processes, cost-effectiveness, and satisfactory performance in current battery technologies. However, as the energy density requirements for EVs and other applications increase, there is a notable shift towards silicon-based anodes. Silicon offers a theoretical capacity approximately ten times that of graphite, making it an attractive alternative despite challenges related to volume expansion and cycle stability (according to the report: Silicon Anode Materials Market, Global Outlook and Forecast 2025-2032).

6. Limitations, challenges, and future directions of anode materials

Despite the remarkable advancements in nanotechnology-driven LIB anodes, several limitations persist. The large-scale commercial synthesis of nanostructured anode materials is often constrained by the high complexity and cost of fabrication processes. Silicon and transition metal oxides are two examples of nanomaterials that lose their mechanical strength and capacity when they go through charge-discharge cycles because their volumes expand a lot. Nanoparticles also don't last long because they have a lot of surface area, which makes side reactions with the electrolyte stronger and speeds up the formation of unstable solid-electrolyte interphase (SEI) layers. These challenges underscore the need for further material optimization and cost-effective manufacturing techniques [103, 104].

Several challenges must be addressed before nanotechnology-driven LIB anodes achieve widespread adoption. The trade-off between high energy density and long-term cycling stability remains a critical issue, requiring innovative design strategies. The capacity of energy storage facilities utilizing LIBs has rapidly increased due to the industry's strong growth in this sector. Concurrently, incidents of fire in battery energy storage systems have also risen, leading to heightened scrutiny over the safety of energy storage solutions [105]. Safety concerns related to thermal runaway, and electrolyte compatibility also need urgent attention [106]. Effective thermal control and robust resistance to runaway thermals are crucial for the thermal safety of battery packs [107, 108]. Methods for battery thermal management, aimed at maintaining the battery within an optimal temperature range, have been extensively studied through various trials. These systems comprise air cooling [109, 110], liquid cooling [111, 112], and phase change material (PCM) cooling systems [100]. Moreover, large-scale production of nanostructured anodes must overcome challenges related to cost, reproducibility, and material availability. Regulatory and sustainability considerations will also play a crucial role in determining the feasibility of these advanced materials for commercial deployment. Addressing these challenges through interdisciplinary collaboration between material scientists, engineers, and industry stakeholders will be essential for the future success of nanotechnology-enhanced LIBs [113].

Solid-state batteries (SSBs) are unable to efficiently employ pure micron-sized silicon as an anode material because of considerable volumetric expansion. Composite anodes that include sulfide binders, conductive carbon, and nano-silicon present significant potential for diverse applications. Integrating a Li-Si anode with stiff carbon may yield significant breakthroughs, but it would also substantially elevate production costs. An additional investigation into thicker binders is crucial for creating a resilient silicon composite anode that reduces volumetric expansion and prolongs the cycle life of silicon-based solid-state batteries [2]. The "zero strain" $Li_4Ti_5O_{12}$ demonstrates exceptional cycle performance, swift charging and discharging capabilities, elevated potential, and the lack of a solid electrolyte interphase (SEI) layer and lithium dendrite formation, with its remarkable reversibility. Nonetheless, $Li_4Ti_5O_{12}$ faces manufacturing challenges and exhibits low energy density. Silicon materials exhibit significant volumetric expansion and suboptimal cycling performance. Graphite-silicon composite materials, known for their exceptional cycle stability, have become the predominant selection. To enhance their initially low efficiency, silicon-oxygen/carbon anodes necessitate pre-lithiation. Lithium metal theoretically has the largest specific capacity, lowest density, and lowest electrode potential. Nonetheless, challenges such as anode precipitation, side reactions, and lithium dendrite formation impede battery safety [97, 99]. Efficient modification techniques, including nanoparticle incorporation, composite formation, doping, and surface treatments, can alleviate these challenges while providing new advantages. The design and production of anode materials must account for factors including weight and volume capacity, cost-effectiveness, resource availability, electrolytes, additives, and adhesives. High-performance anode materials must exhibit exceptional stability, extended longevity, rapid charging and discharging rates, and superior overall performance. Ongoing advancements in the formulation, modification, and optimization of anode materials are essential. Innovative anode materials, exemplified by MXn alloy reaction anodes where M represents a transition metal and X signifies a non-metal are garnering attention. Researchers are investigating transition metal compounds produced via conversion methods, nitrides, and non-metallic composites. Structural enhancements, including synthetic interface layers, optimized pore topologies, and surface coatings, can further enhance anode performance. Advanced manufacturing techniques, including three-dimensional printing and topological optimization, enable the creation of complex electrode structures. Enhancing the current collector by the incorporation of flame retardants, the use of multi-layer designs, and the use of ultra-thin, lightweight materials can improve battery efficiency. The manufacture of batteries is a complex and detailed field [100]. Graph theory, artificial intelligence, and machine learning offer solutions for addressing data and parameter challenges in the advancement of LIBs. These advancements may enable the creation of next-generation battery technologies that exceed traditional electrochemical cells and LIBs. The growing need for high-performance, environmentally sustainable batteries in various industries poses new opportunities and challenges for lithium battery development. Actively pursuing novel materials and technologies is crucial for fostering the sustainable development of lithium batteries with improved durability, power density, and energy density [102].

The future prospects for anode materials in LIBs are influenced by the necessity of developing energy storage solutions that combine high capacity, extended cycle life, and cost-effective production. Therefore, carbon-based anode materials, such as graphite, have dominated the market due to their excellent electrical conductivity and stable cycling performance. However, the quest for higher energy densities necessitates exploring alternatives [15]. Accordingly, Tin/silicon-based materials also present a promising alternative, offering high theoretical capacities. As mentioned earlier, the primary challenge with Sn/Si anodes is their significant volume change during lithiation, leading to mechanical degradation. Thus, the current development is focusing on creating both Sn and Si-based composites and alloys that can accommodate these volume changes and improve cycling stability [46, 114]. Looking ahead, the development of hybrid anode materials that integrate the benefits of different material classes may offer a path to overcoming individual limitations. Additionally, the ongoing exploration of solid-state electrolytes could revolutionize anode material performance by mitigating issues related to liquid electrolyte decomposition and dendrite formation [5]. The integration of materials engineering and electrochemical optimization is expected to enhance the performance of tin-based anodes, enabling their application in next-generation LIBs with superior efficacy.

Conclusions

The development of advanced anode materials plays a pivotal role in enhancing LIB performance. Advanced anode materials play a key role in enhancing the performance of LIBs, with high-capacity candidates like silicon and tin offering significant potential. However, these materials face persistent issues such as poor stability, low electrical conductivity, and high production costs, which necessitate innovative solutions like structural modifications, doping techniques, and surface coatings. The review also highlights the future prospects and challenges in LIBs. Ongoing research remains vital for advancing next-generation LIBs that are safer, more durable, and capable of delivering superior performance. Nanotechnology has revolutionized the development of anode materials for LIBs, enabling significant improvements in capacity, cycling stability, and rate performance. Nanostructured materials, including carbon-based (graphene, CNTs), silicon, metal oxides, and transition metal compounds, have demonstrated enhanced electrochemical properties by mitigating volume expansion, improving electron/ion transport, and increasing active surface area. Additionally, composite and hybrid materials integrate the advantages of multiple nanomaterials, further optimizing anode performance. Despite these advancements, challenges such as structural degradation, unstable solid electrolyte interphase (SEI), and high manufacturing costs persist. Future research should focus on scalable synthesis methods, novel nanomaterial designs, and electrolyte engineering to achieve long-term stability and commercial viability.

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Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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