

A Comprehensive Analysis of Molybdenum-Based Materials for High-Efficiency Anodes in Lithium-Ion Batteries

Ashaq Hussain^{1*}, Rabia Javed² and Altaf Ahmed³

^{1,3} Department of Chemistry, GGM Science College Jammu, J&K

² Department of Chemistry, PSPS Govt College for Women, Gandhi Nagar Jammu J&K

*Correspondence: joinchemistry@gmail.com

Abstract

High-energy rechargeable metal ion batteries are thought to be the most promising power source for electric vehicles (EVs) how ever one significant problem, though, is finding appropriate anode materials that can stably and reversibly host metal ions. Alkali metals batteries due to their high specific capacities, and low reduction potentials are thought to make the ideal anodes for next-generation and molybdenum-based nanomaterials have drawn interest as electrode materials for these alkali metal-ion batteries (AMIBs) due to their huge theoretical capacity and other technological advantages. However, the large volume changes and delayed reaction kinetics that lead to structural collapse degrade their electrochemical performance. This review provides an insight of the development of Mo-based anodes for next-generation lithium-ion batteries. Developments in the synthesis and design of Mo-based compounds for LIBs are critically examined in this review. Furthermore, we aim to provide an extensive overview of the morphologies and properties of Mo-based materials, for creating high-performance Mo-based designs in LIBs.

Key Words: Electric Vehicle, Lithium ion battery, Molybdenum anode, Metal ion batteries, Rechargeable battery

Introduction

Rapid economic development and the corresponding increase in energy consumption have accelerated the depletion of fossil fuel reserves and significantly intensified CO₂ emissions. To conserve non-renewable resources and mitigate environmental impacts, substantial progress has been made toward transitioning from a fossil fuel-based economy to a clean and sustainable energy economy [1–3]. Extensive research efforts are focused on harnessing renewable energy resources such as solar, wind, and geothermal energy [4,5]. However, the intermittent and fluctuating nature of these energy sources necessitates the development of efficient and reliable energy storage systems (ESSs) for large-scale deployment. Among various ESS technologies, alkali metal-ion batteries (AMIBs) have emerged as highly promising candidates owing to their reliability, environmental compatibility, and cost-effectiveness. These batteries are widely used in portable electronics, electric vehicles (EVs), and smart grid applications [6,7].

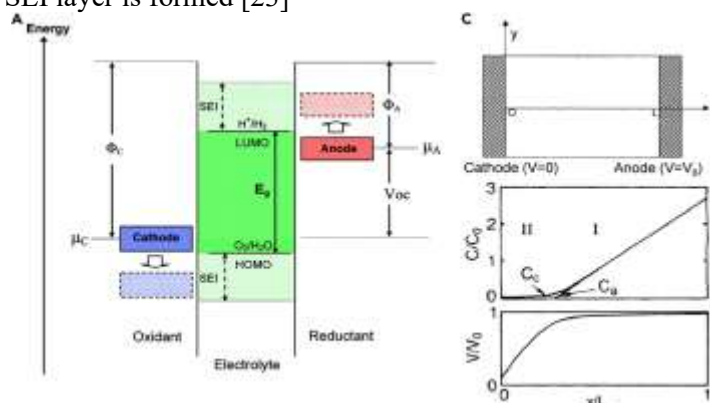
Since their commercial introduction in 1991, lithium-ion batteries (LIBs) have become the most successful class of AMIBs and are now indispensable in modern energy storage technologies [8]. Their high energy density, long cycle life, and low self-discharge have revolutionized portable electronics and enabled widespread adoption in EVs and grid-scale storage systems. Nevertheless, the rapid growth in LIB demand has raised concerns regarding the limited natural abundance and uneven geographical distribution of lithium, which constitutes only 0.0017 wt.% of the Earth's crust, compared with 2.36 wt.% and 2.09 wt.% for sodium and potassium, respectively [9,10]. In addition, the performance of LIBs is strongly influenced by electrode materials, particularly the anode, which governs capacity and overall efficiency [11].

To overcome these limitations, sodium-ion batteries (SIBs) and potassium-ion batteries (PIBs) have gained significant attention as sustainable alternatives due to the abundance and low cost of Na and K resources [12–14]. Since electrode materials, especially anodes, play a decisive role in achieving high energy density, the development of adaptable and high-performance anode materials is essential for advancing AMIB technologies [15]. Commercial graphite, the most widely used anode material in LIBs, suffers from a relatively low theoretical capacity, resulting in energy densities of only 120–150 Wh kg⁻¹ at the battery-pack level [17]. Furthermore, the larger ionic radii of Na⁺ (1.02 Å) and K⁺ (1.38 Å), compared with Li⁺ (0.76 Å), induce substantial volume expansion during cycling, leading to structural degradation and rapid capacity fading [16].

IMPLICATIONS ON LITHIUM ANODES

The energy storage mechanism of sodium-ion batteries (SIBs) is fundamentally similar to that of lithium-ion batteries (LIBs). However, their energy density is generally lower because of limited specific capacities and a smaller potential difference between the cathode and anode. In practical full-cell configurations, the standard reduction potential of sodium (–2.71 V vs. standard hydrogen electrode, SHE) is approximately 0.3 V higher than that of lithium (–3.04 V vs. SHE), resulting in a reduced cell voltage and consequently lower energy density [18]. In contrast, potassium possesses a much lower standard potential (–2.936 V vs. SHE), very close to that of lithium, enabling potassium-ion batteries (PIBs) to potentially achieve higher energy densities.

PIBs are considered promising alternatives to LIBs owing to the high ionic conductivity of K^+ and the natural abundance of potassium resources. Nevertheless, their practical application is hindered by the high chemical reactivity of alkali metals and the instability of the solid electrolyte interphase (SEI). Since alkali metals occur only in compound form in nature, they are highly sensitive to moisture and gradually degrade even in dry air, posing significant challenges for handling and characterization [19–21]. Moreover, these metals readily react with polar aprotic solvents, salt anions, and dissolved cathode species, leading to poor cycling stability [22]. During the initial charge–discharge cycles, SEI films form on Na and K anodes. Good and Kim proposed that when the lowest unoccupied molecular orbital (LUMO) of the electrolyte lies below that of the anode, electrons are transferred to the electrolyte, causing its reduction until a passivating SEI layer is formed [23]



According to reports, SEI coatings act as a barrier to prevent additional degradation of the electrolyte caused by alkali metal reduction. In the absence of the protective layer, the interaction between alkali metals and electrolytes increases, leading to the rapid consumption of both [24]. According to reports, this is what caused the CE to drop sharply, yet the recovered SEI shows higher impedance and greater thickness [25,26].

Dendrite Expansion and Significant Volume Shift

The unexpected dendritic growth commonly observed on alkali metal anodes is primarily attributed to the non-uniform deposition of alkali metals during repeated plating and stripping processes. In certain cases, dendrite formation may also occur in “alkali-metal-free” cells, particularly under high current densities and low-temperature conditions [27]. These dendritic structures not only reduce electrochemical performance but also pose serious safety concerns, as they may penetrate the separator and reach the cathode, leading to internal short circuits, thermal runaway, fire, or even explosion [28].

Several mechanisms have been proposed to explain dendrite nucleation and propagation on lithium metal. According to the surface nucleation and diffusion model, Li atoms tend to remain isolated rather than agglomerate, which thermodynamically favors dendrite formation [29]. In addition, rapid Li deposition in dilute electrolytes causes a sharp decrease in anion concentration near the electrode surface, generating a local space-charge region and an intense electric field that promotes dendritic growth [30]. Therefore, an ideal solid electrolyte interphase (SEI) should possess high mechanical strength, optimal thickness, high ionic conductivity, and electronic insulating characteristics to regulate uniform ion flux and accommodate volume changes. These limitations have driven extensive research into advanced secondary battery technologies. Progress in morphological design, synthesis strategies, and theoretical modeling has significantly improved the understanding and performance of lithium-ion batteries (LIBs) [29].

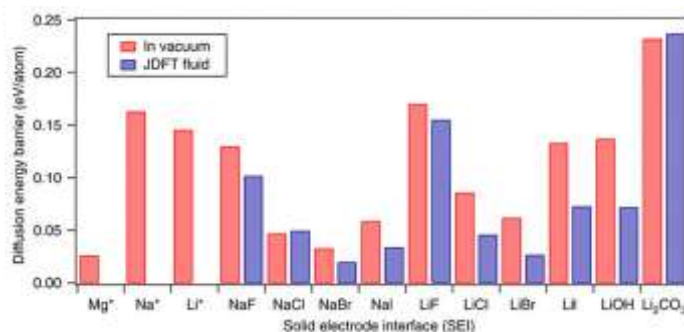


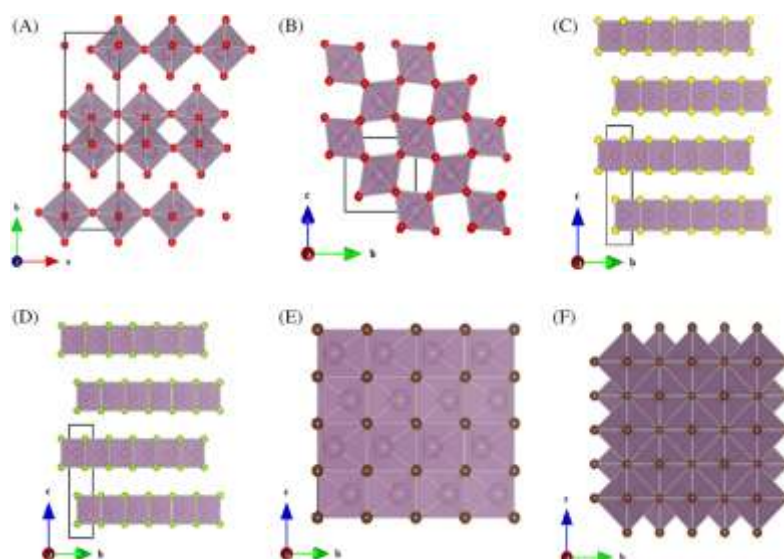
Figure: Fundamental Principles of SEI Formation and Schematic of a Space-Charge Model of Li Dendrite Nucleation

Significant research efforts have recently focused on the development of versatile, high-capacity electrode materials for large-scale applications of aqueous metal-ion batteries (AMIBs) [19,20]. Various modification strategies have been explored, including nano-sizing of host materials, heteroatom doping, integration with fast ion conductors, and the

introduction of structural defects. Among these, nano-sizing has proven particularly effective in optimizing electrode performance [31]. Nanoscale materials offer tunable surface area, hierarchical porosity, and abundant internal space, all of which are highly advantageous for energy storage applications. Compared with conventional anode materials such as carbon (C), antimony (Sb), copper (Cu), and vanadium (V)-based systems, molybdenum (Mo)-based materials exhibit superior electrical conductivity, robust crystal structures, facile synthesis, and low toxicity [32,33]. This review systematically examines recent advances in Mo-based materials for lithium-ion batteries (LIBs), covering design principles, synthesis strategies, charge-storage mechanisms, and electrochemical performance. It also discusses current challenges and outlines future directions for the development of advanced Mo-based electrode systems.

Mo-BASED ANODE MATERIALS

In recent years, there has been a lot of interest in anode materials based on transition metal elements. Material based on molybdenum (Mo) in particular has been considered a viable electrode material because of its distinct structural and performance advantages, MoS_2 and MoO_2 have become attractive materials for negative electrodes because of their distinct architectures and high specific capacitance [34]. The majority of Mo materials have a high theoretical capacity due to intercalation and/or conversion processes, and also Molybdenum is cheap and plentiful in the earth's crust. Furthermore, Mo-based compounds, such as oxides (MoO_3 , MoO_2), dichalcogenides (MoS_2 , MoSe_2), and carbides (Mo_2C , MoC) exhibit extensive structural chemistry with a range of stoichiometries due to their numerous valence states with different coordination numbers[34-36]. The following figure shows their representative crystal formations.



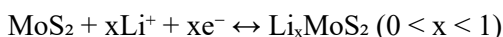
Crystal structures of (A) orthorhombic $\alpha\text{-MoO}_3$, (B) monoclinic MoO_2 , (C) hexagonal 2H-MoS_2 , (D) hexagonal 2H-MoSe_2 , (E) orthorhombic Mo_2C , and (F) hexagonal MoC

It has been demonstrated that using an asymmetric membrane structure in conjunction with other active materials is a practical way to produce high-capacity anode materials for both lithium-ion and sodium-ion batteries[37]. Both nanoparticles and nanobelts embedded in an asymmetric membrane can be used as stable, high-capacity electrodes. Selecting the right polymer and conductive additive can result in special qualities including higher capacity, better cycling performance, and superior conductivity. Thus, the performance of the anodes has been found to be significantly influenced by the polymer selection, surface coating, and active material concentration/morphology. These factors offer viable substitutes for energy storage devices that are currently on the market and advance our knowledge of LIBs anode materials. Some of these are summarized as under;

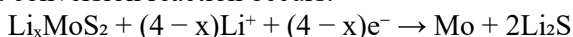
Molybdenum Disulphides

Molybdenum disulfide (MoS_2) is regarded as a highly promising anode material for high-performance lithium-ion batteries (LIBs) because of its unique layered crystal structure and attractive electrochemical properties. Similar to graphite, MoS_2 consists of covalently bonded two-dimensional S–Mo–S layers held together by weak van der Waals interactions, which facilitate lithium-ion intercalation while maintaining structural integrity[38]. Depending on the arrangement of Mo and S atoms and the stacking sequence of adjacent layers, MoS_2 exists in several polymorphs, including trigonal 1T-MoS_2 , rhombohedral 3R-MoS_2 , and hexagonal 2H-MoS_2 [39]. Its abundance of electrochemically active sites and high theoretical capacity make it an excellent LIB electrode material[40].

Within the voltage window of 3.0–0.01 V versus Li/Li^+ , lithium storage in MoS_2 proceeds through two sequential steps. The first involves reversible Li^+ intercalation between 3.0 and 1.1 V:



Insertion of one Li atom per Mo atom yields LiMoS_2 , corresponding to a theoretical capacity of 167 mAh g^{-1} . Below 1.1 V, a conversion reaction occurs:

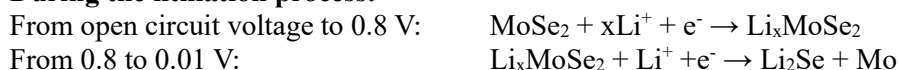


Despite these advantages, MoS_2 suffers from poor intrinsic electrical conductivity and substantial volume expansion during cycling, which can lead to capacity fading and poor rate performance.

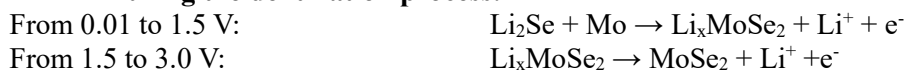
Molybdenum selenide

A typical 2D material, MoSe_2 has a hexagonal Se-Mo-Se layered crystal structure resembling that of MoS_2 . While mild van der Waals forces hold the layers together, covalent and ionic bonds firmly bind the atoms within each layer. MoSe_2 is an interesting material for lithium storage due to its high interlayer spacing (~ 0.65 nm), short bandgap (~ 1.1 eV), and reasonable capacity (~ 422 mAh g^{-1}) [43]. The results of the ex situ TEM tests carried out to investigate the molecular mechanism of lithiation/delithiation reaction are reported as follows.

During the lithiation process:



During the delithiation process:



Like MoS_2 , MoSe_2 thus has a conventional stepwise procedure. The Li^+ storage mechanism in MoSe_2 as analysed above, showed that MoSe_2 underwent conversion and intercalation reactions involving Li_2Se , MoSe_2 , and Li_xMoSe_2 . The volume significantly increased as a result of these processes. Moreover, MoSe_2 exhibits poor cycle performance and restricted rate capabilities due to its narrow bandgap semiconductor nature and low electronic conductivity of 1.2 eV. However, disagreements about the exact mechanism and reversibility of Se do exist there. Zhang et al. proposed that the released product, Na_2Se , would react with metallic Mo to generate MoSe_2 in the ensuing desodiation phase, despite the fact that this reaction is not very reversible [44].

Molybdenum telluride

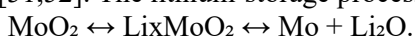
Molybdenum ditelluride (MoTe_2), another member of the molybdenum-based dichalcogenide family, possesses a broad spectrum of tunable properties with significant potential for commercial applications in microelectronics, power devices, microwave technology, and telecommunications [45,46]. As a promising two-dimensional van der Waals material, MoTe_2 exhibits high electronic conductivity and weak interlayer interactions, which facilitate rapid Li^+ insertion and extraction, making it highly suitable for energy storage applications. MoTe_2 exists in two polymorphic phases: monoclinic semimetallic (1T') and hexagonal semiconducting (2H). Panda et al. successfully synthesized 2H- MoTe_2 anodes via a simple solid-state method and investigated the lithium storage mechanism using in situ XANES combined with first-principles DFT calculations, confirming excellent structural stability and electrochemical reversibility [47]. A full cell assembled with LiCoO_2 delivered a high energy density of 454 Wh kg^{-1} and retained 80% of its capacity after 100 cycles, highlighting the promise of MoTe_2 as an efficient anode for LIBs [48]. However, unlike MoS_2 and MoSe_2 , the synthesis of MoTe_2 remains challenging. Therefore, further research is needed to develop efficient synthesis strategies and to design MoTe_2 -based composites through defect and structural engineering.

Molybdenum Oxides

Molybdenum oxides are thought to be potential anode materials for lithium-ion batteries (LIBs) because they exhibit a wide range of electrical properties, from wide band gap semiconducting (MoO_3) to metallic (MoO_2). Examples of these oxides are MoO_3 , $\text{Mo}_n\text{O}_{3n-1}$, and MoO_2 . Compared to graphite, they have substantially larger specific capacities [49,50]. These oxides are inexpensive, widely available, and have a high theoretical specific capacity of roughly 500–1200 mAh g^{-1} because of their conversion reaction during lithiation. Continuous efforts, including nanostructure engineering, complexing Mo-based materials with carbonaceous matrix, heterostructure creation, and heteroatom doping, have been made to achieve the appropriate structure, morphology, and composition of Mo-based materials for LIBs. In the context of battery applications, molybdenum trioxide (MoO_3) and dioxide (MoO_2) are two common compounds that have drawn a lot of interest.

Molybdenum dioxide (MoO_2)

Recent advances have generated significant interest in understanding the Li^+ storage mechanism of MoO_2 . Numerous studies have employed multishelled MoO_2 architectures as high-performance anode materials for lithium-ion batteries (LIBs) [51,52]. The lithium-storage process proceeds through a combined intercalation and conversion mechanism:



The lithiation behavior of MoO_2 is strongly governed by the crystallinity and surface characteristics of the electrode, which may cause slight shifts in redox peak positions. However, the near invariance of these peaks during repeated charge–discharge cycles indicates highly reversible phase transitions. During the conversion reaction, the Mo–O bond is weakened, thereby facilitating Li^+ diffusion in Mo-based materials. Despite these advantages, sluggish reaction kinetics and substantial volume changes during lithiation and delithiation often lead to poor cycling stability and rapid capacity fading. Consequently, considerable efforts have been directed toward nanostructure engineering, carbonaceous composite formation, and heteroatom doping to improve electrochemical performance.

Nanostructuring effectively shortens Li^+ diffusion paths, reduces internal stress, and enhances reaction kinetics. MoO_2 has been synthesized in diverse morphologies, including nanowires, nanotubes, nanorods, and nanobelts. Although one-dimensional structures have shown promising results, Guo et al. reported that larger feature sizes (>100 nm) limit electrochemical performance [53]. Merely reducing particle size does not fully mitigate volume expansion; instead, hierarchical porous structures offer superior accommodation of structural strain while increasing electrode–electrolyte contact. Porous hierarchical MoO_2 nanotubes prepared by a simple carbothermal reduction method exhibited outstanding specific capacity and rate capability [54]. Hollow and core–shell architectures further enhance performance. In particular, composites with carbonaceous materials such as graphene, carbon aerogels, amorphous carbon, and carbon fibers improve conductivity and buffer volume changes. MoO_2 /carbon aerogel composites provide internal void space and accelerated charge transport, yielding layered porous structures with excellent electrochemical properties [55,56].

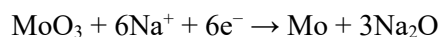
Graphene, an atomically thin carbon material with exceptional electrical conductivity and high specific surface area, has emerged as an ideal support for MoO_2 . MoO_2 nanoparticles anchored on three-dimensional graphene (MoO_2 -3DG) were synthesized by reducing MoO_3 nanobelts [57,58]. When grown on nickel foam, the interconnected graphene network maintains its porous architecture and uniformly disperses MoO_2 nanoparticles, enabling binder-free electrodes without additional conductive additives.

Another effective strategy is heteroatom doping with elements such as N, B, P, and S. Doping introduces structural defects, enhances conductivity, and increases electrochemically active sites. Nitrogen doping is particularly effective because of the similar atomic size and chemical compatibility of nitrogen and carbon. Porous N-doped carbon nanotubes encapsulating MoO_2 nanostructures preserve structural integrity at high current densities and promote intimate electrolyte contact [59].

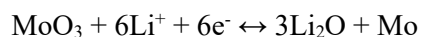
These studies highlight nitrogen-doped carbon/ MoO_2 hybrid nanomaterials as highly promising LIB anodes. Compared with molybdenum chalcogenides, MoO_2 offers greater commercial potential because of its high efficiency and low cost. Future research should focus on scalable and high-yield synthesis approaches, especially microwave-assisted methods, to enable commercial production of carbon-integrated Mo-based electrode materials.

Molybdenum trioxide(MoO_3)

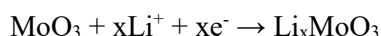
MoO_3 is the popular Mo-based anode that has been the subject of much research as a promising anode material for Li-ion batteries (LIBs) because of its adaptable structure, low cost, nontoxicity, natural abundance, adjustable chemical state, high thermal and chemical stability, environmental friendliness, and good theoretical capacity of 1117 mAh/g—three times that of commercial graphite (327 mAh/g)[60–63]. There are three distinct crystal structures for MoO which are hexagonal (h-MoO_3), monoclinic ($\beta\text{-MoO}_3$), and orthorhombic ($\alpha\text{-MoO}_3$). Because of its unique layered structure, $\alpha\text{-MoO}_3$ is the most stable phase from a thermodynamic perspective, which makes it a good fit for LIBs[64,65]. The electrochemical storage of Li/Na ions in MoO_3 has been extensively studied. The insertion process, which functions in the voltage range of 1.0–4.0 V, is the main mechanism for Li^+/Na^+ ion storage in MoO_3 . A decrease potential of about 2.4 V vs Na/Na^+ , in particular, indicates the formation of a sodium bronze (Na_xMoO_3). Then, at a lower potential, this bronze will decrease to $\text{Na}_x + z\text{MoO}_3$ [66]. In addition, within the potential range of 0.01 to 3 V, MoO_3 acts as an anode and undergoes both insertion and conversion processes during the sodiation process with a theoretical capacity of 1117 mAh g^{-1} . The over all reaction can be written as;



Because of the significant volume swelling that happens when Na^+ ions are added, this reaction is not highly reversible [67]. However, to understand the Li^+ storage property of MoO_3 -based electrodes, it is essential to understand the basic reaction mechanism of the lithiation/dethiation process. In the potential window of 0.01–3.0 V, MoO_3 undergoes the transition reaction as follows:



Further research has also indicated that the reaction mechanism can be explained by fully atomistic first-principles molecular dynamics calculations in two steps as;



and $\text{Li}_x\text{MoO}_3 + (6-x)\text{Li}^+ + (6-x)\text{e}^- \leftrightarrow 3\text{Li}_2\text{O} + \text{Mo}$.

The Li^+ storage mechanism in Molybdenum Trioxide has been elucidated through cyclic voltammetry (CV) studies. The cathodic peaks observed at approximately 2.5 V and 2.15 V correspond to Li^+ intercalation and the subsequent conversion reaction leading to the formation of Li_xMoO_3 , while the broad plateau near 0.5 V is attributed to the complete conversion of Li_xMoO_3 into metallic Mo and Li_2O [68]. To enhance the electrochemical performance of MoO_3 in lithium-ion batteries (LIBs), numerous nanostructured morphologies—including nanosheets, nanowires, nanorods, nanofibers, and nanobelts—have been extensively investigated. For instance, high-quality MoO_3 nanorods and nanoflowers have been synthesized using a simple ultrasound-assisted aqueous solution method, whereas $\alpha\text{-MoO}_3$ sheets with highly exposed crystallographic planes were fabricated via a one-step thermal plasma process, offering deeper insight into the atomic-scale microstructural evolution of MoO_3 [69,70].

The electrical conductivity and overall electrochemical performance of MoO_3 electrodes have also been significantly improved by incorporating conductive carbonaceous materials such as carbon nanotubes, graphene, and reduced graphene oxide. Owing to their large specific surface area and high aspect ratio, carbon nanotubes are particularly effective in constructing MoO_3 -based nanotube-like composites with enhanced electrochemical properties [71]. Furthermore, vertically aligned MoO_3 nanosheets anchored on graphene nanolayers through a nucleation-growth strategy effectively suppress aggregation, stabilize the electrode architecture, and provide abundant channels for Li^+ transport, thereby accelerating reaction kinetics [72].

Similar to Molybdenum Dioxide, nitrogen-doped carbon materials are widely employed in MoO_3 engineering to improve electrical conductivity and introduce additional active sites for Li^+ insertion/extraction. For example, MoO_3 nanosheets encapsulated within an ultrathin N-doped carbon layer were synthesized via pyrolytic reduction using dodecylamine as both carbon and nitrogen sources [73]. Although these strategies markedly enhance Li^+ storage performance, rational structural design alone cannot fully prevent the rapid capacity fading associated with structural degradation. Therefore, the development of robust protective coatings, including conductive polymers and amorphous layers deposited by atomic layer deposition, remains essential for preserving structural integrity and achieving long-term cycling stability.

Conclusion

Lithium-ion batteries (LIBs) have emerged as the leading energy storage technology for a wide range of applications, including electric vehicles, portable electronics, and large-scale energy storage systems. Among the various components of LIBs, the anode material plays a decisive role in determining the battery's capacity, cycling stability, rate capability, and overall efficiency. Although conventional graphite-based anodes have been widely employed due to their excellent stability and low cost, their limited theoretical capacity has prompted extensive research into alternative materials capable of delivering higher energy densities.

Approximately three decades ago, the lithium-sulfur (Li-S) battery system was introduced as a promising next-generation energy storage technology. However, two major challenges hindered its practical implementation: the polysulfide shuttle effect and the inherently poor electrical conductivity of sulfur. To overcome these issues, researchers incorporated conductive additives such as carbon black and conductive polymers into sulfur cathodes, forming sulfur-carbon and sulfur-conductive polymer composites. Conductive carbon additives, including Super P and high-conductivity carbon black, significantly enhanced electron transport, reduced cathode resistance, and improved active material utilization, thereby increasing battery capacity and overall electrochemical performance.

Building upon these advances in conductive materials, molybdenum-based compounds have attracted considerable attention as promising alternatives to traditional graphite anodes in lithium-ion batteries. These materials possess several desirable characteristics, including high theoretical capacities, excellent electrical conductivity, superior rate performance, and enhanced structural stability. Among them, Molybdenum disulfide (MoS_2) has been extensively studied because of its layered structure, rapid lithium-ion diffusion kinetics, high specific capacity, and remarkable cycling stability. Similarly, Molybdenum dioxide (MoO_2) and Molybdenum trioxide (MoO_3) have demonstrated efficient and reversible lithium storage behavior with improved electrochemical characteristics.

One of the principal advantages of molybdenum-based materials is their ability to alloy with lithium and form various intermetallic compounds, resulting in significantly higher specific capacities than conventional graphite anodes. This high theoretical capacity offers substantial potential for increasing the energy density of lithium-ion batteries, making them suitable for high-energy applications. In addition, the excellent intrinsic electrical conductivity of molybdenum-based materials facilitates rapid electron transport during charging and discharging, thereby reducing internal resistance and enhancing charge-transfer efficiency. Furthermore, their robust structural integrity helps mitigate electrode pulverization, suppress volume expansion, and maintain the stability of the electrode architecture, ultimately contributing to prolonged cycle life and superior long-term performance.

Despite these notable advantages, several challenges remain. Extensive studies on molybdenum-based anodes for alkali metal-ion batteries (AMIBs) conducted from 2009 to 2023 indicate that substantial volume changes, sluggish reaction kinetics, surface instability, and irreversible capacity loss are the primary limitations. Repeated insertion and

extraction of Li^+ ions can induce severe structural degradation, causing active materials to detach from the current collector and resulting in diminished electrochemical performance.

To address these shortcomings, numerous strategies have been developed. Nanostructuring approaches, such as the fabrication of porous and hollow architectures, effectively shorten ion diffusion pathways and accommodate volume changes. Carbon modification creates conductive networks that accelerate electron transport and buffer mechanical stress. Heteroatom doping introduces lattice disorder, modifies electronic structures, and enhances intrinsic conductivity. Additional techniques, including surface coating, alloying, and the formation of composite materials, have further improved the stability and electrochemical performance of molybdenum-based anodes.

In conclusion, molybdenum-based materials represent highly promising high-performance anodes for lithium-ion batteries due to their exceptional capacity, superior conductivity, and robust structural stability. Significant progress has been achieved in recent years, particularly in the development of advanced AMIBs. Continued research and innovation are expected to unlock the full potential of molybdenum-based anodes and pave the way for the next generation of advanced metal-ion battery technologies.

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