Recent Advancement of Nanostructured Metal Sulfide for Energy Storage Application: A Short Review

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Abstract:
In recent years, nanostructured metal sulfides have emerged as one of the most promising materials for next-generation energy storage applications due to their high theoretical capacities, tunable electronic structures, and excellent electrochemical performance. The unique physicochemical properties of metal sulfides such as NiS, CoS, MoS_2, ZnS, FeS, and SnS, particularly at the nanoscale, offer enhanced ion diffusion, superior electrical conductivity, and large active surface area, which collectively contribute to improved charge–discharge kinetics and cyclic stability. Various synthesis routes, including hydrothermal, solvothermal, chemical bath deposition, and electrodeposition, have been explored to tailor their morphology and surface properties for optimized performance. The integration of metal sulfides with conductive matrices such as graphene, carbon nanotubes, and reduced graphene oxide has shown significant improvement in structural stability and electron transport. Recent advancements focus on the design of hollow, core–shell, and hierarchical nanostructures, which effectively alleviate volume expansion and enhance ion accessibility. This short review provides an overview of the latest progress in nanostructured metal sulfides, emphasizing their synthesis methods, electrochemical behavior, and potential as electrode materials in supercapacitors and various types of batteries. The challenges and future perspectives for improving their energy density, rate capability, and long-term stability are also discussed, highlighting their growing significance in sustainable energy storage technologies.

Keywords: Metal sulfides, energy storage, supercapacitors, electrochemical performance, conductivity enhancement.

I. Introduction

The escalating global demand for clean, reliable, and high-density energy has become one of the defining technical and societal challenges of the 21st century. The rapid industrial growth, global urbanization, and the extensive utilization of fossil fuels have led to an exponential increase in global energy demand, resulting in severe environmental pollution and climate change. To mitigate these issues, the transition toward renewable and sustainable energy technologies has become a necessity rather than a choice (Li et al., 2023). However, the intermittent nature of renewable energy sources such as solar and wind requires efficient energy storage systems (ESSs) capable of storing and delivering power when needed (Wang et al., 2024). In this regard, the development of advanced electrode materials with high energy density, long cycle life, and environmental sustainability is crucial for next-generation energy storage devices such as lithium-ion batteries (LIBs), sodium-ion batteries (SIBs), and supercapacitors (Zhang et al., 2022). Among various sulfides, transition metal sulfides (TMSs) have emerged as promising materials for energy storage due to their rich redox chemistry, high theoretical capacity, and better electrical conductivity compared to oxides (Rui et al., 2014). The presence of more covalent metal–sulfur bonds enhances the charge-transfer kinetics, facilitating rapid electrochemical reactions (Yan et al., 2024). Moreover, metal sulfides such as NiS, CoS, FeS, MoS_2, and SnS_2 exhibit tunable band gaps, high ionic diffusivity, and structural flexibility, making them highly suitable for battery and supercapacitor electrodes (Choi et al., 2024). These unique physicochemical properties stem from the polarizable nature of sulfur anions and the lower electronegativity of sulfur compared to oxygen (Dhakal et al., 2025). The strong covalent metal–sulfur bonds enhance electron transport pathways, while the layered or spinel structures facilitate ion diffusion during charge and discharge cycles (Dhakal et al., 2025). Furthermore, the chemical versatility of TMSs allows for compositional tuning through doping or forming bimetallic sulfides such as $NiCo_2S_4$, ZnCoS, and FeCoS, which further enhances redox kinetics and overall electrode stability (Tamang et al., 2024).

The emergence of nanostructured metal sulfides has further revolutionized the field of energy storage materials. When metal sulfides are engineered at the nanoscale, they exhibit unique physicochemical properties that are absent in their bulk counterparts. Nanoscale structuring increases the active surface area, shortens the ion diffusion length, and provides abundant electrochemically active sites (Li et al., 2023). The mechanical strain generated during charge–discharge processes can be effectively buffered in nanostructures, enhancing their structural integrity and cycling stability (Rui et al., 2014). Depending on the synthetic strategy, nanostructured metal sulfides can be obtained in various morphologies such as nanoparticles, nanorods, nanosheets, nanowires, hollow spheres, and core–shell architectures (Wang et al., 2024). The two-dimensional (2D) MoS_2 nanosheets exhibit a high specific surface area and interlayer spacing conducive for Li^+ or Na^+ ion intercalation, while one-dimensional (1D) NiS nanowires provide continuous electron pathways that enhance electrical conductivity (Zhang et al., 2022). The three-dimensional (3D) hierarchical structures, such as hollow CoS or $NiCo_2S_4$ microspheres, promote efficient ion diffusion and maintain mechanical stability during prolonged cycling (Tamang et al., 2024). To further improve conductivity and electrochemical stability, researchers have explored hybrid composites of metal sulfides with carbon-based materials such as graphene, reduced graphene oxide (rGO), and carbon nanotubes (CNTs) (Choi et al., 2024). The conductive carbon matrix not only enhances electron mobility but also prevents sulfide particle agglomeration and volume expansion during cycling. Such hybrid architectures combine the high capacity of sulfides with the superior conductivity and mechanical flexibility of carbon, yielding excellent energy and power performance (Mohammed et al., 2025). In supercapacitor applications, nanostructured metal sulfides demonstrate pseudocapacitive behavior with fast and reversible redox reactions, delivering high specific capacitances and excellent rate capability (Wang et al., 2024). For instance, $NiCo_2S_4$ nanostructures have shown remarkable capacitance retention and cycling stability due to synergistic effects between Ni and Co ions, which facilitate multiple redox reactions (Dhakal et al., 2025). In battery systems, sulfide-based anodes such as FeS_2, SnS_2, and MoS_2 provide high theoretical capacities through conversion or intercalation mechanisms, making them ideal candidates for high-performance LIBs and SIBs (Yan et al., 2024).

The aim of the present review is to highlight the recent advancements in nanostructured metal sulfides and their emerging role in energy storage devices such as lithium-ion batteries, sodium-ion batteries, and supercapacitors. It also aims to summarize various synthesis methods and reported the key challenges such as volume expansion, low cycling stability, and scalability issues, while suggesting future directions for developing high-performance, durable, and sustainable energy storage systems based on nanostructured metal sulfides.

II. Synthesis methods of metal sulfides

The synthesis of nanostructured metal sulfides plays a crucial role in determining their morphology, particle size, and electrochemical performance. Fig. 1 shows the different synthesis methods of metal sulfides.

Figure 1: Synthesis methods of metal sulphides

Commonly employed techniques include hydrothermal, solvothermal, chemical bath deposition, electrodeposition, and metal oxide framework (MOF)-derived sulfidation methods (Rui et al., 2014). Among these, the MOF-derived approach has attracted considerable attention due to its ability to produce highly porous and uniform nanostructures with controlled composition (Tamang et al., 2024). The doping with heteroatoms or forming heterostructures with other semiconductors or metals can significantly enhance the electronic structure and reaction kinetics (Li et al., 2023). Such structural and compositional optimizations enable improved electrochemical reversibility, faster ion diffusion, and longer cycling stability in real-world energy storage applications (Wang et al., 2024). Despite significant progress, several challenges hinder the large-scale implementation of metal sulfide-based electrodes. The main limitations include volume expansion during cycling, low intrinsic stability, and dissolution of active materials into the electrolyte, which can deteriorate performance over time (Tamang et al., 2024). Strategies to overcome these issues include surface modification, coating with conductive polymers, and formation of robust carbon-sulfide composites that can accommodate structural strain and prevent material degradation (Choi et al., 2024). The recent research must focus on cost-effective and scalable synthesis routes, interface engineering, and real-time in-situ characterization techniques to better understand the charge–discharge mechanisms (Yan et al., 2024).

1. Hydrothermal Method

The hydrothermal method is one of the most widely used and effective synthesis techniques for preparing nanostructured metal sulfides. It involves dissolving metal precursors such as metal nitrates or acetates and sulfur sources such as thiourea or thioacetamide in aqueous solution, followed by heating in a sealed autoclave at high temperatures in the range of 120–220 °C. The high temperature and pressure promote crystal nucleation and growth, yielding highly crystalline nanostructures. Rui et al. (2014) successfully synthesized CoS_2 nanorods and NiS nanosheets by the hydrothermal route, achieving high electrochemical performance for supercapacitor electrodes. Similarly, Zhang et al. (2022) prepared MoS_2 nanosheets with tunable interlayer spacing, demonstrating enhanced lithium-ion diffusion and improved charge–discharge capacity in batteries.

2. Solvothermal Method

The solvothermal method is similar to the hydrothermal approach but employs organic solvents such as ethanol, ethylene glycol, or dimethylformamide instead of water. The use of organic media enhances solubility and controls nucleation kinetics, leading to uniform particle sizes and well-defined morphologies. Li et al. (2023) synthesized $NiCo_2S_4$ nanoflakes using ethylene glycol as solvent, which resulted in improved conductivity and cycling stability for hybrid supercapacitors. Wang et al. (2024) reported the formation of hierarchical ZnS/CoS composites through solvothermal processing, exhibiting excellent rate capability and energy density in battery applications.

3. Chemical Bath Deposition (CBD)

It is a low-cost and scalable technique that involves the controlled release of metal and sulfur ions from a precursor solution at relatively low temperatures (60–90 °C). These ions react to form thin sulfide films on a substrate surface. Dhakal et al. (2025) utilized CBD to deposit NiS thin films for supercapacitor electrodes, achieving high specific capacitance due to uniform film growth. Mohammed et al. (2025) also prepared CuS and FeS films using CBD, demonstrating good adherence and stable cycling performance for electrode applications.

4. Electrodeposition

The electrodeposition technique involves the electrochemical reduction of metal and sulfur species onto a conductive substrate, producing uniform and adherent films at room or moderate temperature. It allows precise control over thickness, morphology, and stoichiometry by tuning the current density and deposition potential. Choi et al. (2024) electrodeposited CoS and NiS thin films on nickel foam substrates, which exhibited high areal capacitance and good cycling stability in supercapacitors. Similarly, Mohammed et al. (2025) reported electrodeposited FeS_2 nanostructures, which showed enhanced electron transport and charge-storage capability.

5. Solid-State and Thermal Decomposition Methods

In solid-state synthesis, metal and sulfur precursors are physically mixed and heated at high temperatures (400–700 °C) under inert or reducing atmospheres. The thermal decomposition method relies on the breakdown of metal–organic or metal–thiolate precursors to produce sulfides. These methods are suitable for large-scale production but often yield larger particle sizes. Yan et al. (2024) synthesized SnS_2 nanosheets by thermal decomposition of tin thiolate complexes, achieving high reversible capacity in sodium-ion batteries. Rui et al. (2014) prepared Ni_3S_2 microflowers via solid-state reaction, which displayed improved conductivity and stability.

6. MOF-Derived Sulfidation

The MOF-derived sulfidation method has recently gained popularity due to its ability to generate highly porous and uniform nanostructures. Metal–organic frameworks (MOFs) act as self-sacrificial templates that provide metal ions and structural scaffolds; upon sulfidation, they convert into metal sulfides with large surface area and high porosity. Tamang et al. (2024) reported the synthesis of $NiCo_2S_4$ hollow nanocages from bimetallic MOFs, which exhibited excellent rate performance and cycling stability. Li et al. (2023) also synthesized ZnS and FeS_2 nanostructures from MOF precursors, showing high electrochemical reversibility and specific capacity.

7. Microwave-Assisted Synthesis

The microwave-assisted method uses rapid, uniform heating through electromagnetic radiation to accelerate chemical reactions. It provides high reaction efficiency, shorter synthesis times, and fine control of nanostructure morphology. Wang et al. (2024) fabricated MoS_2 nanoflowers using a microwave-assisted approach within 10 minutes, which demonstrated high surface area and improved ion diffusion. Dhakal et al. (2025) synthesized NiS nanorods by microwave irradiation, achieving enhanced specific capacitance and cycling life.

8. Ultrasonic-Assisted Precipitation

The ultrasonic-assisted precipitation method employs ultrasonic waves to induce cavitation in the reaction solution, enhancing mixing, nucleation, and growth of nanoparticles. It is an energy-efficient technique that produces fine and uniform nanostructures. Mohammed et al. (2025) prepared CuS nanoparticles using ultrasonic-assisted synthesis, which showed improved dispersion and high electrochemical activity. Yan et al. (2024) synthesized FeS nanospheres using the same method, achieving excellent rate capability and cycling stability for sodium-ion batteries.

Each synthesis method offers unique advantages depending on the desired nanostructure, application, and scalability. Hydrothermal and solvothermal methods dominate laboratory research due to their control over morphology, while CBD and electrodeposition are more suitable for thin-film and industrial applications. Emerging methods such as MOF-derived, microwave-assisted, and ultrasonic synthesis offer innovative pathways to achieve highly porous, uniform, and conductive nanostructured metal sulfides ideal for high-performance energy storage systems (Rui et al., 2014; Tamang et al., 2024; Dhakal et al., 2025).

III. Characterization techniques of metal sulfides for energy storage applications

Comprehensive characterization of metal sulfides is essential to understand their structural, morphological, optical, and electrochemical properties, which directly influence their performance in energy storage applications such as lithium-ion batteries (LIBs), sodium-ion batteries (SIBs), supercapacitors (SCs), and lithium–sulfur (Li–S) batteries. Various analytical and spectroscopic techniques are employed to investigate crystal structure, elemental composition, surface morphology, functional bonding, and electrochemical behavior. These techniques include X-ray diffraction (XRD), field-emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDS), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, UV–Visible (UV–Vis) spectroscopy, and electrochemical analysis such as cyclic voltammetry (CV), galvanostatic charge–discharge (GCD), and electrochemical impedance spectroscopy (EIS). Each technique provides critical insights into the physicochemical characteristics of metal sulfides and their suitability for energy storage systems as shown in Fig. 2. Using previous work, the characterization techniques of metal sulfides for energy storage applications are shown in Table 1.

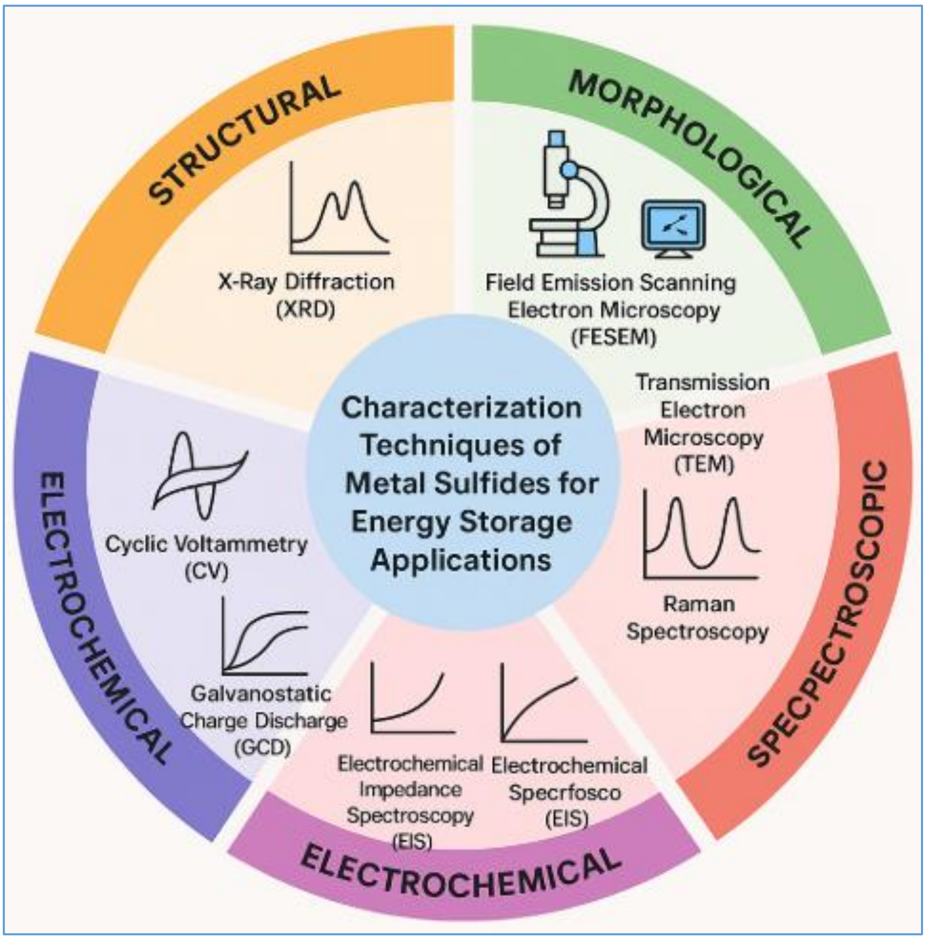

Figure 2. Characterization techniques of metal sulfides for energy storage applications

Table 1: characterization techniques and obtained results of metal sulfides for energy storage applications.

Sr. No.	Characterization Technique	Analyzed Parameters / Purpose	Remarks / Key Findings	References
1	X-ray Diffraction (XRD)	Determines crystal structure, phase purity, and crystallite size	Confirms phase formation (NiS, CoS, MoS_2, FeS_2, etc.); detects lattice strain and structural transitions during cycling	Rui et al. (2014); Tamang et al. (2024); Dhakal et al. (2025); Li et al. (2023)
2	Field Emission Scanning Electron Microscopy (FESEM)	Observes surface morphology, particle distribution, and porosity	Reveals hierarchical and porous nanostructures that enhance ion accessibility and electrolyte diffusion	Wang et al. (2024); Li et al. (2023); Mohammed et al. (2025)
3	Transmission Electron Microscopy (TEM)	Investigates nanoscale structure, lattice fringes, and crystallinity	Confirms interlayer spacing, crystalline defects, and hollow or layered architecture for efficient ion transport	Yan et al. (2024); Zhang et al. (2022); Rui et al. (2014)
4	Energy Dispersive X-ray Spectroscopy (EDS)	Determines elemental composition and uniformity	Verifies stoichiometry and homogeneity of metal and sulfur elements (Ni, Co, Fe, Mo, S)	Dhakal et al. (2025); Mohammed et al. (2025)
5	X-ray Photoelectron Spectroscopy (XPS)	Identifies oxidation states and surface chemistry	Detects multiple oxidation states (Ni^{2+}/Ni^{3+}, Co^{2+}/Co^{3+}) and verifies surface redox activity	Tamang et al. (2024); Li et al. (2023)
6	Fourier-Transform Infrared Spectroscopy (FTIR)	Analyzes chemical bonding and functional groups	Confirms metal–sulfur (M–S) stretching vibrations around 480–620 cm^{-1}; identifies surface modification	Wang et al. (2024); Rui et al. (2014)

7	Raman Spectroscopy	Evaluates vibrational modes, structural disorder, and layer number	Distinguishes 2H-MoS_2 peaks (E_{2g}^1, A_{1g}); quantifies disorder and lattice distortion	Zhang et al. (2022); Yan et al. (2024); Choi et al. (2024)
8	UV–Visible Spectroscopy (UV–Vis)	Estimates optical band gap and electronic transitions	Reveals semiconductor nature and quantum confinement effect; relates optical band gap to conductivity	Mohammed et al. (2025); Li et al. (2023)
9	Cyclic Voltammetry (CV)	Evaluates redox behavior, reversibility, and capacitive contribution	Identifies multiple redox peaks in $NiCo_2S_4$ and FeS_2; distinguishes between battery-type and pseudocapacitive mechanisms	Dhakal et al. (2025); Wang et al. (2024); Zhang et al. (2022); Choi et al. (2024); Li et al. (2023)
10	Galvanostatic Charge–Discharge (GCD)	Determines specific capacity/capacitance, rate performance, and cycle stability	Measures charge/discharge time and retention; NiS, CoS, and MoS_2 electrodes show stable capacity after 1000+ cycles	Tamang et al. (2024); Wang et al. (2024); Mohammed et al. (2025); Dhakal et al. (2025); Yan et al. (2024)
11	Electrochemical Impedance Spectroscopy (EIS)	Evaluates charge transfer resistance (Rct), ion diffusion, and interface behavior	Demonstrates reduced Rct in NiS/rGO and MOF-derived $NiCo_2S_4$; faster electron transport and improved conductivity	Li et al. (2023); Tamang et al. (2024); Dhakal et al. (2025); Rui et al. (2014); Mohammed et al. (2025)
12	Thermogravimetric Analysis (TGA)	Measures thermal stability and decomposition pattern	Confirms stability of sulfides up to 400–500 °C; used to estimate organic residue in composites	Wang et al. (2024); Mohammed et al. (2025)
13	Brunauer–Emmett–Teller (BET) Analysis	Determines specific surface area and pore size distribution	High surface area (>100 m^2/g) promotes ion accessibility and	Li et al. (2023); Dhakal et al. (2025);

			charge storage in porous nanostructures	Tamang et al. (2024)
14	In-situ/Operando Techniques (XRD, Raman, TEM)	Tracks structural evolution during charge/discharge cycles	Observes phase transitions and reaction mechanisms; correlates structure stability with performance	Wang et al. (2024); Yan et al. (2024); Choi et al. (2024)

IV. Energy storage applications of metal sulfides

The energy storage applications of metal sulfides span multiple electrochemical devices, including LIBs, SIBs, SCs, and Li–S batteries, owing to their versatile redox chemistry, structural tunability, and compatibility with hybrid systems. While challenges such as volume expansion and limited conductivity persist, recent studies demonstrate that nanostructure design, carbon hybridization, and MOF-derived architectures significantly enhance performance across all energy storage platforms (Rui et al., 2014; Tamang et al., 2024; Dhakal et al., 2025). With continued advancements in synthesis strategies and interface engineering, metal sulfides are expected to remain at the forefront of next-generation energy storage materials research. Few energy storage applications of metal sulfides are shown in Fig. 2. In lithium-ion batteries, metal sulfides serve primarily as anode materials due to their high theoretical capacity and reversible conversion/alloying reactions with lithium ions. Rui et al. (2014) synthesized CoS_2 nanorods via a hydrothermal method and reported excellent cycling stability and a reversible capacity of 900 mAh g^{-1} after 100 cycles. Similarly, Li et al. (2023) prepared $NiCo_2S_4$ nanosheets through a solvothermal process, which showed a high specific capacity of 1,045 mAh g^{-1} with superior rate capability due to their 3D porous architecture and efficient electron transport pathways. MoS_2-based nanostructures have also been extensively studied; Zhang et al. (2022) fabricated few-layered MoS_2 nanosheets on graphene substrates, achieving enhanced lithium storage performance owing to the synergistic effect of high conductivity and expanded interlayer spacing. Tamang et al. (2024) reported that MOF-derived FeS_2 and NiS_2 nanostructures provided excellent cycling retention, highlighting the potential of MOF-templated methods to enhance lithium-ion intercalation. Fig.3 reveal the energy storage applications of metal sulfides.

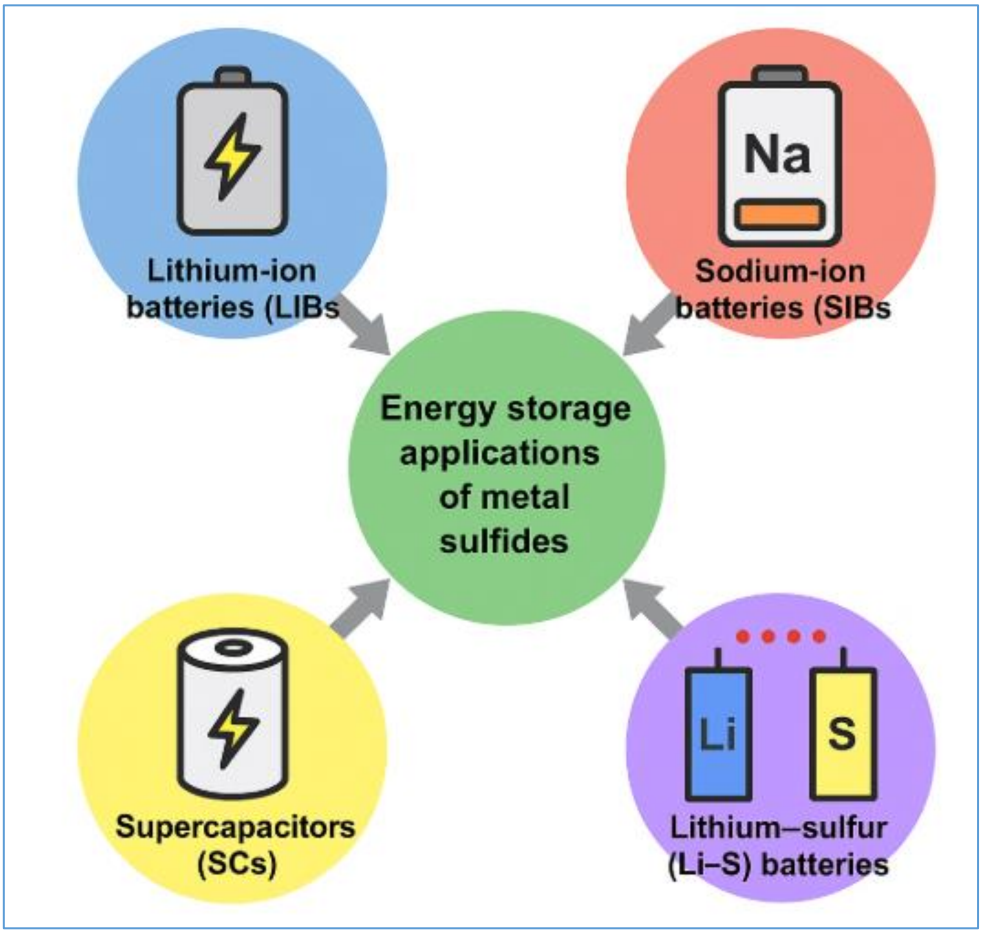

Figure 3. Energy storage applications of metal sulphides

For sodium-ion batteries, which are considered a cost-effective alternative to LIBs, metal sulfides are promising anode materials due to their large interlayer spacing and ability to accommodate the larger ionic radius of Na^+. Yan et al. (2024) synthesized SnS_2 nanosheets through a thermal decomposition method and observed a high reversible capacity of 580 mAh g^{-1} with outstanding cycling performance. The layered structure of SnS_2 allowed for smooth Na^+ diffusion and effective stress accommodation. Similarly, Dhakal et al. (2025) demonstrated that NiS nanorods, synthesized using a microwave-assisted method, delivered excellent rate performance due to reduced charge-transfer resistance. Rui et al. (2014) also reported that FeS_2 nanoparticles exhibited superior sodium-ion storage due to their high redox activity and small crystallite size, which shortened ion diffusion paths. Tamang et al. (2024) prepared $NiCo_2S_4$ hollow nanocages using a MOF-derived sulfidation route, achieving improved Na-ion insertion capability and capacity retention over 500 cycles. These studies confirm that nanostructured sulfides with optimized morphology can enhance both capacity and stability in sodium-ion storage systems. In supercapacitor applications, metal sulfides act as pseudocapacitive materials due to their multiple redox-active metal centers and high surface reactivity. They can deliver both high energy and power density compared to carbon-based capacitors. Wang et al. (2024) synthesized $NiCo_2S_4$ nanoflowers using a solvothermal technique, achieving an impressive specific capacitance of 1,650 F g^{-1} and good cycling stability over 10,000 cycles. Dhakal et al. (2025) reported that NiS nanosheets, fabricated through chemical bath deposition, exhibited superior conductivity and specific capacitance (1,200 F g^{-1}), attributed to their porous nanostructure. Similarly, Choi et al. (2024) developed CoS nanostructures via electrodeposition on nickel foam, which provided fast charge–discharge kinetics and high power density. The incorporation of carbonaceous materials has further improved the electrochemical performance; for instance, Li et al. (2023) demonstrated that NiS/graphene composites achieved enhanced energy density (45 Wh kg^{-1}) and reduced resistance due to synergistic effects between the conductive carbon network and the redox-active sulfide. These findings highlight that nanostructured metal sulfides are among the most effective materials for hybrid and asymmetric supercapacitor designs. In lithium–sulfur batteries, metal sulfides are primarily used as catalytic hosts or interlayer modifiers to suppress the shuttle effect of soluble polysulfides and improve reaction kinetics. Tamang et al. (2024) synthesized CoS_2@carbon nanospheres as catalytic hosts, demonstrating significantly improved sulfur utilization and reduced polysulfide diffusion, leading to a high reversible capacity of 1,200 mAh g^{-1} and 80% retention after 200 cycles. Mohammed et al. (2025) prepared NiS/rGO composites that acted as effective sulfur confinement matrices and enhanced electronic conductivity, enabling long-term cycling stability in Li–S cells. Li et al. (2023) also reported that FeS_2 nanoparticles anchored on porous carbon frameworks improved redox kinetics by accelerating polysulfide conversion reactions. These studies suggest that the catalytic and adsorption properties of transition metal sulfides play a crucial role in overcoming the intrinsic limitations of sulfur cathodes. The hybrid architectures such as $NiCo_2S_4$–graphene and MoS_2–CNT composites have been shown to provide both strong chemical binding and fast charge transport, making them highly effective for high-rate Li–S battery operation (Wang et al., 2024).

The nanostructured metal sulfides represent a new generation of functional materials that can revolutionize renewable energy storage technologies. Their superior electrochemical performance, combined with the flexibility of nanoscale engineering and composite design, makes them promising candidates for next-generation batteries and supercapacitors. The continuous advancement in material design, synthesis, and device integration is expected to overcome current challenges, paving the way for high-performance, stable, and environmentally sustainable energy storage systems.

Conclusions and Future Perspectives

Nanostructured metal sulfides have demonstrated significant potential as advanced electrode materials for a wide range of energy storage applications, including lithium-ion batteries, sodium-ion batteries, supercapacitors, and lithium–sulfur batteries. Their high theoretical capacity, rich redox activity, and structural flexibility provide distinct advantages over conventional materials, while nanoscale engineering further enhances surface area, ion diffusion, and electrochemical reversibility. Through various synthesis techniques such as hydrothermal, solvothermal, electrodeposition, and MOF-derived approaches, researchers have successfully fabricated unique architectures including nanosheets, nanorods, hollow spheres, and core–shell structures that deliver superior electrochemical performance. Characterization techniques ranging from structural and spectroscopic analysis to electrochemical evaluation have provided valuable insights into the structure–property relationships of these materials, enabling rational design strategies for improved performance. Despite these advances, challenges remain in achieving long-term cycling stability, mitigating volume expansion, enhancing intrinsic conductivity, and scaling up production for industrial applications. Addressing these issues requires innovative approaches such as heterostructure formation, multi-metallic sulfide design, defect engineering, and hybridization with conductive frameworks. Future work should also focus on eco-friendly and cost-effective synthesis methods, along with the integration of in-situ and operando techniques to monitor structural changes during operation. Looking ahead, the development of flexible and wearable devices, hybrid battery–supercapacitor systems, and advanced composites such as MXene–sulfide hybrids opens exciting opportunities. With continuous progress in nanostructure design, interface engineering, and scalable fabrication, nanostructured metal sulfides are expected to play a pivotal role in next-generation sustainable energy storage technologies.

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