SIN-CHN SCIENTIFIC PRESS PTE.LTD.

Lithium Battery Engineering and Science 2025, 1(1), 1523.
https://doi.org/10.62617/lbes1523

Article

Advancements and challenges in Lithium-Sulfur (Li-S) batteries: A path toward the next generation of energy storage

Joy Malo[1], Mahajabin Dayna[1], Joya Paul[1], Razu Shahazi[1], Md. Rahim Uddin[1,2], Md. Mahmud Alam[1,*]

[1] Department of Chemical Engineering, Z. H. Sikder University of Science and Technology (ZHSUST), Shariatpur 8024, Bangladesh
[2] Department of Chemical Engineering, College of Environmental Science and Forestry, State University of New York, Syracuse, NY 13210, USA
*** Corresponding author:** Md. Mahmud Alam, alam-mahmud@hotmail.com, mmalam@zhsust.ac.bd

CITATION

Malo J, Dayna M, Paul J, et al. Advancements and challenges in Lithium-Sulfur (Li-S) batteries: A path toward the next generation of energy storage. Lithium Battery Engineering and Science. 2025; 1(1): 1523.
https://doi.org/10.62617/lbes1523

ARTICLE INFO

Received: 10 February 2025
Accepted: 25 February 2025
Available online: 5 March 2025

Abstract: Lithium-sulfur (Li-S) batteries have emerged as a promising next-generation energy storage technology, particularly for electric vehicles (EVs) and large-scale energy storage applications. With the potential for significantly higher energy densities, lower material costs, and improved environmental sustainability, Li-S batteries offer several advantages over traditional lithium-ion (Li-ion) batteries. However, challenges such as low cycle life, poor electrical conductivity, and electrolyte instability have hindered their widespread commercial adoption. This review explores the key benefits of Li-S batteries, including their high theoretical energy density, cost-effectiveness, and environmental friendliness, as well as the technical hurdles that need to be addressed for their practical use. Recent advancements in materials and technology, such as nanostructured sulfur cathodes, polysulfide immobilization, and solid-state electrolytes, are discussed as potential solutions to these challenges. The article concludes by highlighting the future outlook of Li-S batteries, focusing on ongoing research efforts and the potential for Li-S technology to revolutionize energy storage in the coming years.

Keywords: Lithium-sulfur batteries; energy density; electric vehicles; cycle life; polysulfide shuttling; electrolyte stability; sustainable energy storage; next-generation batteries; environmental sustainability

1. Introduction

The growing demand for clean energy solutions, coupled with the rapid rise of electric vehicles (EVs), has intensified the search for advanced energy storage technologies that can offer higher performance, lower costs, and greater sustainability. Traditional energy storage systems, particularly lithium-ion (Li-ion) batteries, have dominated the market for decades due to their reasonable balance of energy density, efficiency, and longevity [1,2]. However, as the world pushes for greener alternatives and seeks to address the limitations of current battery technologies, Lithium-Sulfur (Li-S) batteries have emerged as one of the most promising contenders for the future of energy storage [3,4]. Li-S batteries utilize sulfur as the cathode material and lithium as the anode in **Figure 1**, a combination that offers significantly higher energy density than conventional lithium-ion batteries. The theoretical energy density of Li-S batteries is as much as five times higher than that of traditional Li-ion batteries, making them a potential game-changer for electric vehicles (EVs), grid storage, and portable electronics [5,6]. This would significantly increase the driving range of EVs, lower the cost of EV batteries, and enhance the efficiency of energy storage systems, thereby accelerating the transition to clean energy and reducing reliance on fossil fuels.

In addition to their high energy density, Li-S batteries also have significant cost advantages [7–10]. Sulfur is an abundant, inexpensive material that is widely available and non-toxic, making it an attractive alternative to the rare and often environmentally damaging materials used in Li-ion batteries, such as cobalt and nickel. The shift toward sulfur could drastically reduce manufacturing costs and help lower the overall price of electric vehicles, energy storage systems, and portable devices. This cost-effectiveness, combined with sulfur's environmental sustainability, makes Li-S batteries an appealing option in the context of a global push for greener and more cost-efficient energy solutions [11–13]. However, despite these impressive theoretical advantages, Lithium-Sulfur (Li-S) batteries face several significant challenges that have prevented their widespread commercialization. One of the most pressing concerns is their low cycle life. The sulfur cathode in Li-S batteries undergoes large volume changes during the charge and discharge cycles, which leads to structural degradation and loss of capacity over time [14,15]. Additionally, sulfur forms polysulfides during the discharge process, and these polysulfides are soluble in the electrolyte, causing polysulfide shuttling. This phenomenon results in a loss of active material and leads to rapid capacity fade, significantly reducing the longevity and efficiency of Li-S batteries [16–18].

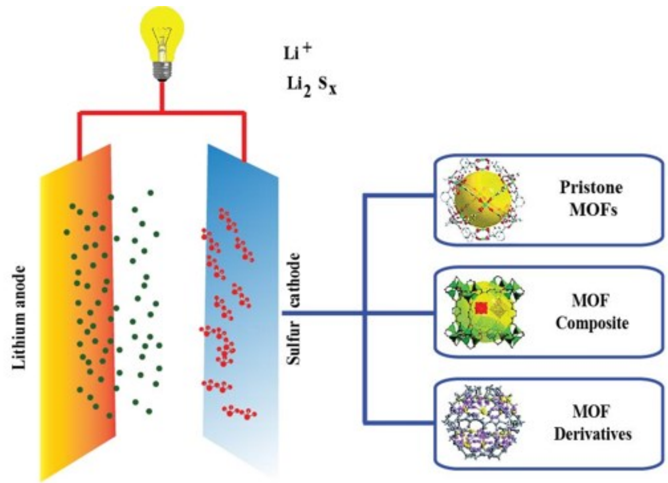

Figure 1. Schematic diagram of lithium-sulfur battery.

Another challenge lies in sulfur's poor electrical conductivity, which reduces the efficiency of the cathode and limits the overall performance of the battery. The use of conductive additives, such as carbon-based materials (graphene, carbon nanotubes), can help mitigate this issue, but this adds complexity and cost to the design of Li-S batteries [19–21]. Furthermore, the instability of electrolytes used in Li-S batteries presents another hurdle. The dissolution of polysulfides into the electrolyte compromises the overall stability of the battery and reduces its operational lifespan [22–24]. Despite these challenges, there has been significant progress in research and development (R&D) to address the inherent limitations of Li-S batteries. Recent advancements in material science, particularly the development of nanostructured sulfur composites, carbon-sulfur composite cathodes, and solid-state electrolytes, have shown promising results in improving the conductivity, cycle life, and stability of Li-S batteries [25,26]. These innovations, alongside breakthroughs in polysulfide trapping technologies, are gradually making Li-S batteries more viable for practical applications. Researchers are also working on improving scalability and manufacturing processes, which are crucial steps toward bringing this promising technology to market. The future outlook for Li-S batteries is highly promising. If the current challenges can be overcome, these batteries could revolutionize the way we store and utilize energy, particularly in sectors such as electric vehicles (EVs), renewable energy storage, and portable electronics. The potential for a substantial reduction in costs, coupled with their higher energy density, could make Li-S batteries a significant player in the global shift toward sustainable energy systems. Furthermore, as the world moves away from environmentally harmful materials like cobalt and nickel, Li-S batteries' environmental sustainability could make them a cornerstone of a cleaner, more sustainable energy future.

This article explores the current progress, challenges, and future prospects of Lithium-Sulfur (Li-S) batteries, with a focus on their potential applications in electric vehicles, energy storage, and consumer electronics. We will examine the key technological advancements that have been made, discuss the remaining challenges that need to be addressed, and highlight the exciting opportunities that Li-S batteries present in the next generation of energy storage technologies.

2. Challenges hindering widespread commercial adoption of Lithium-sulfur (Li-S) batteries

Despite the immense potential of Lithium-Sulfur (Li-S) batteries, their widespread adoption in commercial applications has been hindered by several technical challenges. These challenges primarily involve issues related to cycle life, electrical conductivity, and electrolyte stability. To unlock the full potential of Li-S technology, these obstacles need to be addressed, especially if Li-S batteries are to become a viable solution for applications in electric vehicles (EVs), grid energy storage, and consumer electronics.

2.1. Low cycle life

One of the most significant barriers to the commercialization of Li-S batteries is their low cycle life. Cycle life refers to the number of charge and discharge cycles a battery can undergo before its performance degrades significantly. For Li-S batteries, the cycle life is limited by several factors that result in the gradual loss of capacity over time, making them unsuitable for long-term use [27,28].

2.1.1. Volume expansion and structural degradation

During charging and discharging, sulfur undergoes large volume changes, expanding and contracting as it interacts with lithium. This constant volume change creates mechanical stress within the sulfur cathode, leading to structural degradation, including cracking and fragmentation [29,30]. Over time, this damage causes a loss of active material, reducing the battery's capacity and significantly shortening its lifespan. Innovations in nanostructured sulfur have demonstrated potential in reducing mechanical stress by enhancing the structural integrity of the cathode during its expansion and contraction, as shown in **Figure 2**. Tiwari et al. [31] and Han et al. [32]

described in their review articles that this improvement helps retain active material, ultimately boosting the cycle life.

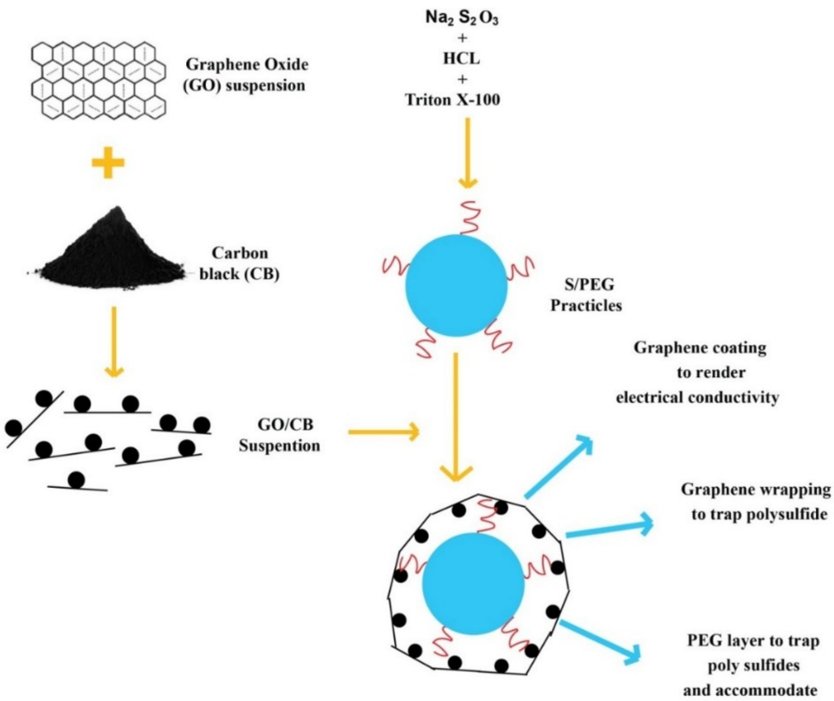

Figure 2. Innovation and progress in nanostructured sulfur cathodes.

2.1.2. Polysulfide dissolution and shuttling

Another major contributor to low cycle life is the formation of polysulfides during discharge. These intermediate compounds are highly soluble in the electrolyte and can dissolve and migrate within the battery, a phenomenon known as polysulfide shuttling [33–35]. Polysulfides that migrate toward the anode can lead to capacity loss, as they do not easily return to the cathode during recharging. This results in a decrease in available active material and an increase in self-discharge, further diminishing the battery's capacity. To mitigate this, materials like carbon nanotubes, metal-organic frameworks (MOFs), and conductive polymers are being explored to trap polysulfides and prevent them from dissolving into the electrolyte, thereby reducing capacity loss [36–38]. Additionally, solid-state electrolytes have been identified as a potential solution to mitigate polysulfide dissolution and enhance overall battery stability. They help prevent the migration of polysulfides and provide better structural integrity throughout extended cycling [39–41].

2.2. Poor electrical conductivity

A major challenge in Li-S batteries is sulfur's inherently low electrical conductivity. As the primary cathode material, sulfur's poor conductivity significantly limits the battery's overall efficiency. This low conductivity results in high internal resistance, making the charge and discharge processes less efficient and reducing the battery's energy output [42–44]. Consequently, sulfur's poor conductivity leads to uneven charge distribution within the cathode, causing inefficient energy storage. Additionally, this uneven distribution creates local hotspots during charge cycles, preventing the full utilization of the sulfur material [45–47]. As a result, the battery's performance, capacity, and efficiency are compromised.

Carbon-based composites

Materials like graphene, carbon nanotubes, and carbon black are being incorporated into the sulfur cathode to create sulfur-carbon composites as seen in **Figure 3**. These composites improve the conductivity of the cathode, enhancing the overall battery performance [48,49]. Zhang et al. [50] and Li et al. [51] reported that sulfur composite materials, such as graphene nanosheets and carbon nanotubes, used as cathodes in lithium-sulfur batteries, significantly improved conductivity and overall performance. In addition, embedding sulfur in porous carbon matrices or combining it with highly conductive carbon materials has enabled researchers to develop more conductive and stable sulfur cathodes. These composites enhance charge transport and improve energy efficiency. Recent studies have shown that nitrogen-rich hierarchical porous carbon paper [52] and porous carbon-based hybridized matrices [53] can significantly enhance charging/discharging capacity and energy storage efficiency in Li-S batteries.

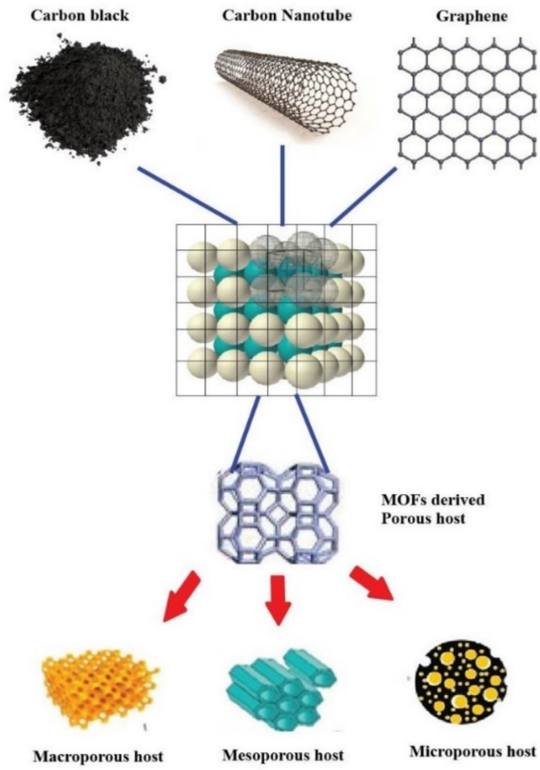

Figure 3. Diagram showing how to prepare a graphene-sulfur/carbon nanotube/carbon black composite with a three-dimensional hierarchical structure.

2.3. Electrolyte instability

The instability of electrolytes in Li-S batteries is another major challenge. When the sulfur cathode forms polysulfides during discharge, these compounds are highly soluble in the electrolyte. The dissolution of polysulfides into the electrolyte leads to electrolyte degradation, which significantly impacts the stability and performance of the battery [54,55] as discussed in part 2 of section 2.1. The instability of the electrolyte can trigger unwanted side reactions, leading to the degradation of the battery's components, such as anode corrosion. The dissolution of polysulfides and their interaction with the electrolyte further deteriorate its performance over time, causing a reduction in battery efficiency and an increase in self-discharge. This degradation also diminishes the battery's charge retention, ultimately shortening its lifespan and lowering its overall effectiveness [56,57]. To address these issues, several strategies are being investigated, as discussed below.

2.3.1. Innovative electrolyte formulations

The development of non-aqueous electrolytes, such as ionic liquids or gel polymer electrolytes, can help stabilize polysulfides and prevent their dissolution. These new electrolytes enhance the overall performance and stability of the battery [58,59]. As reported in recent years, a gel polymer electrolyte (GPE) made from polymer ionic liquid (PIL) is used in both solvent-free and hybrid electrolyte configurations for Li-S batteries. The solvent-free configuration demonstrates a high discharge capacity during the initial cycle and excellent coulombic efficiency in subsequent cycles, showing a discharge capacity of 1217.7 $mAh \cdot g^{-1}$. After 20 cycles at a current density of 50 $mA \cdot g^{-1}$, it maintains a reversible capacity of 818 $mAh \cdot g^{-1}$ [60,61].

2.3.2. Solid-state electrolytes

The integration of solid-state electrolytes eliminates the issue of polysulfide dissolution entirely, as shown in **Figure 4**. Solid-state batteries are inherently more stable than their liquid-based counterparts, offering greater safety and durability [62,63]. Tan et al. [64] found that Li–In | Li_6PS_5Cl | $Li6PS_5Cl$–C half-cells exhibit reversible cycling, providing a capacity of 965 $mAh \cdot g^{-1}$ for the electrolyte material. During charging, Li_6PS_5Cl is oxidized, forming sulfur (S) and phosphorus pentasulfide (P_2S_5). Upon discharge, these products are reduced to a Li_3PS_4 intermediate, which is then converted into lithium sulfide (Li_2S) and lithium phosphide (Li_3P) [64].

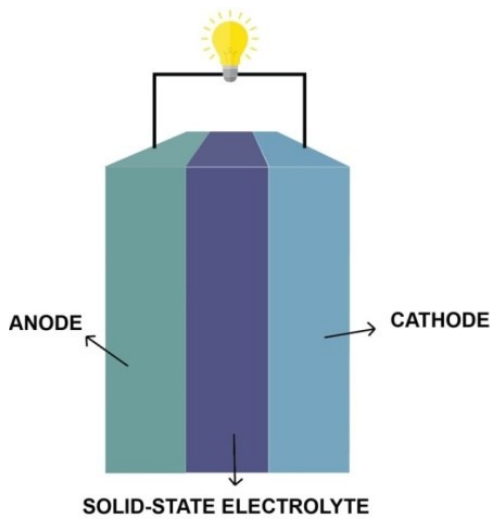

Figure 4. Schematic representation of the solid-state electrolyte in Lithium-sulfur batteries.

2.3.3. Electrolyte additives

Specific additives can be introduced to the electrolyte to chemically bind with polysulfides, preventing their migration and reducing their detrimental effects on battery performance [65,66]. Recently, electrolyte additives such as Benzoselenol [67], metal iodides (LiI, MgI_2, AlI_3, TiI_4, and SnI_4) [68], and isomeric organodithiol [69] have been utilized, demonstrating high charging and discharging capacities.

Lithium-sulfur (Li-S) batteries offer significant potential in terms of energy density, cost-effectiveness, and environmental sustainability compared to traditional lithium-ion batteries. However, challenges such as low cycle life, poor electrical conductivity, and electrolyte instability must be addressed before Li-S batteries can be widely adopted for commercial applications. Researchers are actively developing solutions, including polysulfide trapping, nanostructured sulfur composites, and solid-state electrolytes, which are gradually overcoming these barriers. With ongoing advancements, Li-S batteries hold the promise of revolutionizing energy storage, particularly for electric vehicles, grid energy storage, and consumer electronics, paving the way for a more sustainable and cost-effective future in energy storage technology.

3. Recent progress in Lithium-sulfur (Li-S) battery research

In recent years, Lithium-sulfur (Li-S) batteries have gained significant attention from the scientific community due to their exceptional theoretical advantages, including high energy density, low cost, and environmental sustainability. While commercial adoption of Li-S technology has been hindered by several challenges, recent research efforts have yielded promising advancements that address some of the most critical issues, such as low cycle life, poor electrical conductivity, and electrolyte instability. These developments are bringing us closer to realizing the full potential of Li-S batteries in large-scale applications, including electric vehicles (EVs), grid storage, and consumer electronics.

3.1. Enhancements in cycle life and stability

One of the most significant challenges for Li-S batteries is low cycle life, primarily due to the polysulfide dissolution and the volume expansion of sulfur during cycling. Recent progress in this area has focused on improving the structural stability of the sulfur cathode and preventing the dissolution of polysulfides into the electrolyte [70,71].

Polysulfide trapping strategies

Nanostructured carbon materials: Researchers have developed innovative carbon-based materials, such as carbon nanotubes (CNTs), graphene, and porous carbon frameworks, to trap polysulfides and prevent their dissolution. These materials act as physical barriers, anchoring the polysulfides to the cathode and enhancing the overall cycle stability [72,73]. In 2023, Wang et al. [74] and Kwon et al. [75] made a significant advancement by designing mesoporous carbon-sulfur composites that create a stable network for polysulfides, effectively preventing their migration to the anode.

Metal-organic frameworks (MOFs): MOFs are another promising solution, offering a highly porous structure with a large surface area that can effectively absorb and trap polysulfides. This strategy has been shown to minimize polysulfide shuttling, significantly improving the cycle life and efficiency of Li-S batteries. In 2021, Cai et al. [76] and Kang et al. [77] proposed that metal-organic frameworks (MOFs) provide abundant nanopores and a large surface area, making them effective for trapping polysulfide species.

Solid-state electrolytes: A notable recent development is the integration of solid-state electrolytes into Li-S batteries. Solid-state electrolytes offer superior stability compared to liquid electrolytes and help reduce polysulfide dissolution [78,79]. Solid-state Li-S batteries also eliminate issues related to electrolyte leakage and flammability, making them safer than their liquid counterparts [80,81]. Researchers are investigating a range of solid electrolytes, including sulfide-based and oxide-based materials, to improve the conductivity and stability of Li-S systems.

3.2. Improvement in electrical conductivity

The low electrical conductivity of sulfur remains a major challenge for Li-S batteries, as it results in inefficient charge and discharge cycles. Researchers have made significant strides in enhancing the conductivity of sulfur cathodes [82,83].

3.2.1. Sulfur-carbon composites

Graphene and CNTs integration: A promising approach to improving conductivity involves creating sulfur-carbon composites, where sulfur is combined with highly conductive materials like graphene or carbon nanotubes is seen in **Figure 5**. These composites enhance electron conductivity and facilitate better charge transfer throughout the cathode [84,85]. For example, a graphene-sulfur composite has been developed, showing significant improvements in conductivity, electrochemical performance, and cycle stability. Zhang et al. [86] and Wei et al. [87] highlighted that sulfur nanocrystals anchored on graphene composites, as well as graphene/sulfur/polyaniline ternary composites, significantly enhanced the conductivity, electrochemical performance, and cycle stability of Li-S batteries.

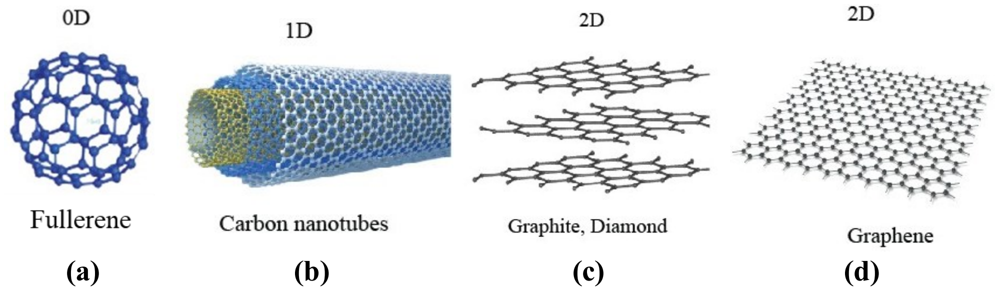

Figure 5. Structure of **(a)** fullerene; **(b)** carbon nanotubes; **(c)** graphite; and **(d)** graphene.

Porous carbon structures: Porous carbon materials, such as activated carbon or carbon black, have been integrated with sulfur to create composite materials with excellent electrical conductivity. These materials also provide a high surface area for sulfur, enabling better utilization of the active material and improving overall battery performance [88,89]. Bora et al. [90] and Khodabakhshi et al. [91] reported that activated carbon and carbon black are effective materials for enhancing the conductivity of Li-S batteries.

3.2.2. Conductive polymer coatings

Conductive polymers, like polyaniline or polypyrrole, have been employed as coatings to improve the conductivity of sulfur particles. These polymers form a conductive network around the sulfur particles, improving electron flow and reducing the internal resistance of the battery. This development has shown promising results in enhancing the power density and overall performance of Li-S batteries [92,93].

3.3. Innovations in electrolyte design

To overcome the issue of electrolyte instability and polysulfide dissolution, researchers have explored various innovations in electrolyte design.

3.3.1. Ionic liquid electrolytes

The use of ionic liquids as electrolytes has gained attention due to their high thermal stability, wide electrochemical window, and low volatility, as shown in **Figure 6.**

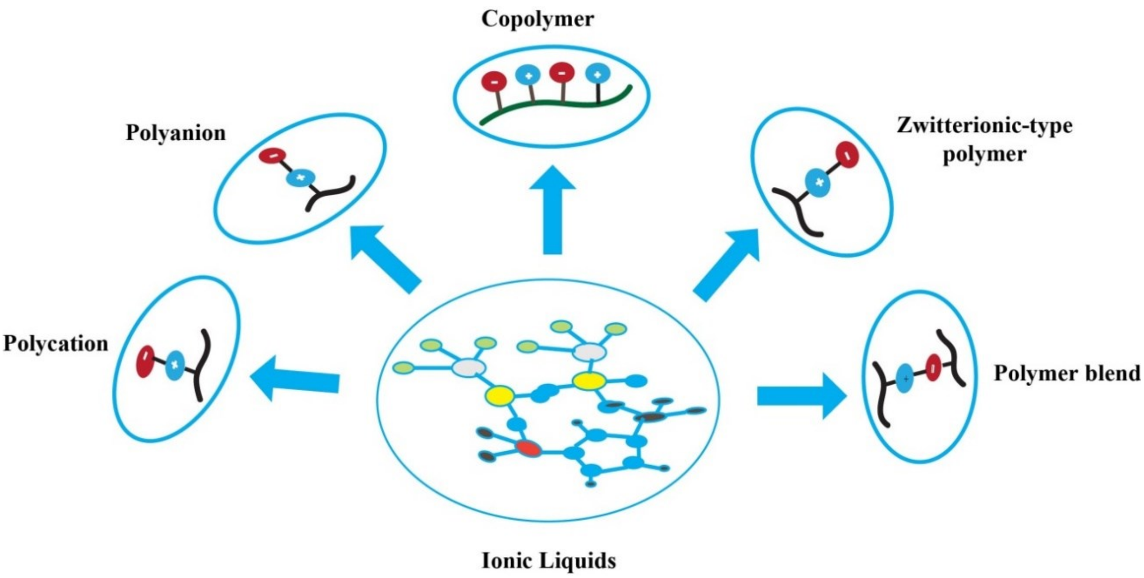

Figure 6. Schematic diagram an ionic liquid electrolyte.

Zheng et al. [94] and Pal et al. [95] observed that ionic liquid electrolytes minimize the dissolution of polysulfides into the electrolyte, thereby enhancing the overall efficiency and stability of Li-S batteries. Additionally, ionic liquids are non-flammable, which enhances the safety of the battery.

3.3.2. Gel polymer electrolytes

Another breakthrough in electrolyte development is the use of gel polymer electrolytes (GPEs). These materials combine the advantages of both solid and liquid electrolytes by offering flexibility, high conductivity, and enhanced stability. GPEs help mitigate polysulfide dissolution and improve the interface between the sulfur cathode and the electrolyte, leading to better performance over extended cycles [96,97].

3.4. Advanced cathode designs and structural modifications

Another promising area of research is the design of novel cathode structures that improve the capacity and stability of the sulfur cathode. Some of the key advancements include:

3.4.1. Nanostructured sulfur cathodes

The development of nanostructured sulfur cathodes, such as sulfur nanospheres or sulfur nanowires, helps mitigate the mechanical stresses caused by volume expansion during cycling. These nanostructures can accommodate the expansion of sulfur without compromising the overall integrity of the cathode, leading to longer cycle life and better performance [98,99]. Gao et al. [100] and Zhou et al. [101] explained that sulfur nanowires and nanofiber cathodes help reduce mechanical stresses in Li-S batteries.

3.4.2. Multilayer cathodes

Researchers are also exploring multilayer cathodes, where sulfur is embedded in layers of carbonaceous materials or conductive polymers, as seen in **Figure 7**. These multilayered structures help improve the overall conductivity of the cathode, provide better structural support, and reduce the risk of polysulfide dissolution [102,103]. Shi et al. [104] and Huang et al. [105] developed multilayer sulfur-embedded cathodes for Li-S batteries, which effectively reduced polysulfide dissolution.

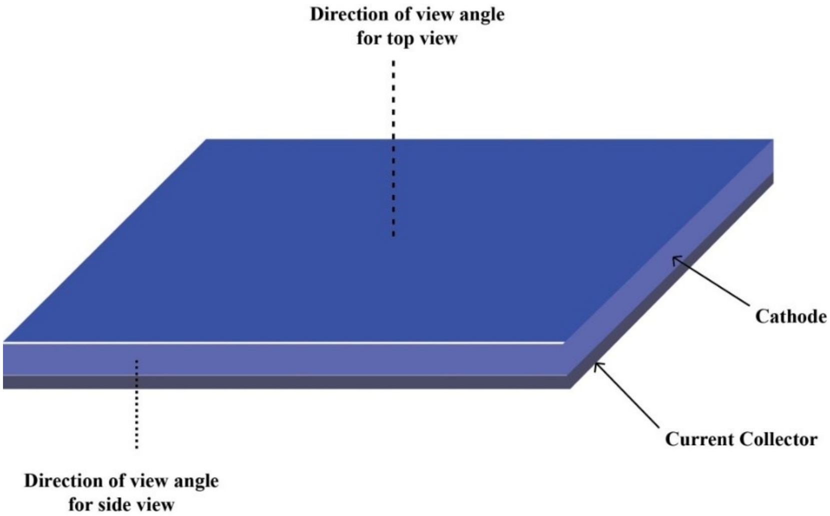

Figure 7. Schematic illustration of a multi-layer cathode.

3.5. Scaling up and commercialization efforts

While research has shown promising improvements in the performance of Li-S batteries in lab settings, scaling up these technologies for large-scale applications remains a challenge. Recent efforts in this area focus on developing cost-effective manufacturing processes and improving the scalability of sulfur-based materials.

3.5.1. Cost-effective manufacturing

Research efforts are underway to develop low-cost, scalable methods for synthesizing high-quality sulfur-carbon composites and other advanced materials used in Li-S batteries. By optimizing the production process and utilizing abundant materials like sulfur, researchers aim to bring down the cost of Li-S batteries, making them more economically viable for mass-market adoption [106,107].

3.5.2. Cell and system integration

Additionally, significant progress is being made in integrating Li-S batteries into full-cell configurations that demonstrate practical performance. Researchers are focusing on optimizing the balance between sulfur cathodes, lithium anodes, and electrolytes to create systems that can perform efficiently under real-world conditions. This includes addressing challenges related to thermal management, safety, and packaging for commercial applications like EVs and greenhouse storage [108,109].

Thus, recent research in Lithium-Sulfur (Li-S) batteries has yielded significant advancements that have addressed some of the most pressing challenges, such as low cycle life, poor conductivity, and electrolyte instability. Innovations in polysulfide trapping, sulfur-carbon composites, solid-state electrolytes, and novel cathode designs are paving the way for Li-S batteries to achieve their theoretical potential in energy density, cost-effectiveness, and sustainability. The advantages and disadvantages of Li-S batteries are explored in **Table 1**. While challenges remain in scaling up these technologies for mass-market use, ongoing research is moving toward overcoming these hurdles, making Li-S batteries a promising candidate for future energy storage solutions in electric vehicles, renewable energy storage, and consumer electronics.

Table 1. The advantages and disadvantages of Li-S batteries.

Advantages	Disadvantages
(i) Li-S batteries offer high power output and efficiency, thanks to carbon materials.	(i) Use of expensive materials like CNTs and graphene.
(ii) Faster charge/discharge rates, ideal for high-power applications.	(ii) Excessive conductive material can lower sulfur content, reducing energy density.
(iii) Longer cycle life due to high conductivity.	(iii) Improved conductivity can lead to more polysulfide dissolution, causing capacity loss.
(iv) Reduced energy losses, minimizing heat generation.	(iv) Conductive materials may interact with the electrolyte, triggering side reactions.
(v) Lower polarization with higher conductivity, improving efficiency.	(v) Additives in the electrolyte can impact battery weight, size, and form factor.
(vi) Better structural stability prevents sulfur dissolution and volume expansion.	(vi) High conductivity still risks polysulfide dissolution, leading to capacity loss.
(vii) Faster charging and discharging, crucial for high-power needs.	(vii) Electrochemical stability of sulfur degrades over cycles, affecting long-term performance.
(viii) Sulfur provides a theoretical energy density of about 500 Wh/kg, higher than traditional lithium-ion batteries.	(viii) Sulfur undergoes significant volume expansion during charge/discharge cycles, causing capacity fading.
(ix) Sulfur's lightweight helps reduce battery weight, beneficial for applications like electric vehicles.	(ix) Polysulfide dissolution during cycling reduces active material, lowering efficiency and lifespan.
(x) The addition of carbon materials (e.g., graphene, CNTs) boosts sulfur cathode conductivity, enhancing performance.	(x) Volume changes during cycling can damage the structure, compromising cathode integrity.
(xi) Sulfur-carbon composites offer superior energy storage due to sulfur's high theoretical capacity (1675 mAh/g).	

4. Future research directions for Lithium-sulfur (Li-S) batteries

Despite the significant progress made in recent years, Lithium-Sulfur (Li-S) batteries still face several challenges that need to be addressed before they can be widely adopted in commercial applications. Future research directions are focused on tackling these challenges and optimizing Li-S technology for large-scale, practical use in fields such as electric vehicles (EVs), grid storage, and consumer electronics. The following outlines some of the key areas for future research in Li-S batteries:

4.1. Enhancing cycle life and durability

Improving the cycle life of Li-S batteries remains one of the primary challenges. The dissolution of polysulfides and the volume expansion of sulfur during cycling degrade the performance over time. Research should continue to focus on:

4.1.1. Advanced polysulfide management

While significant progress has been made with carbon-based materials (e.g., carbon nanotubes, graphene, and metal-organic frameworks), further innovations in polysulfide trapping are needed. Research into more efficient and cost-effective materials that can absorb and stabilize polysulfides during cycling will be critical.

4.1.2. Multifunctional cathodes

Combining sulfur with highly conductive carbon frameworks or metal oxides that also bind polysulfides could help prevent their dissolution, minimizing the loss of active material. New cathode structures that can accommodate sulfur's volume changes without compromising stability are also a key focus.

4.1.3. Volume expansion mitigation

Nanostructured sulfur: Developing nano-sized sulfur particles or using nanostructured sulfur composites that better withstand the mechanical stress of volume expansion will be essential for improving cycle life. Further exploration of sulfur composites, such as sulfur embedded in conductive porous networks, can enhance the material's structural integrity during cycling.

4.2. Improving electrical conductivity

The poor electrical conductivity of sulfur is one of the major limiting factors in the performance of Li-S batteries. Future research in this area will likely focus on:

4.2.1. Advanced conductive additives and composites

Graphene-based composites: Graphene has shown great promise in improving the conductivity of sulfur cathodes. Future research could explore graphene-based hybrid materials, combining graphene with other conductive materials (e.g., metallic nanoparticles or conductive polymers) to further enhance the conductivity and electrochemical performance.

4.2.2. Porous carbon and carbon nanotubes

Researchers should continue to focus on designing high surface-area, porous carbon materials and carbon nanotubes that provide efficient electron transport pathways. These materials not only improve conductivity but also offer structural support to the sulfur cathode.

4.2.3. Conductive polymer coatings

The use of conductive polymers like polyaniline or polypyrrole should be expanded for use as coatings for sulfur cathodes. Future research could focus on creating self-healing conductive polymer layers that would remain intact over many charge-discharge cycles, further improving stability and performance.

4.3. Developing stable electrolytes

Electrolyte instability is another major challenge that needs to be addressed for Li-S batteries to become commercially viable. Future research efforts in this area will focus on:

4.3.1. Polysulfide-resistant electrolytes

While ionic liquids have shown promise, research should focus on improving their conductivity and compatibility with lithium metal anodes. The development of ionic liquid-based electrolytes that are not only resistant to polysulfide dissolution but also operate efficiently at high charge/discharge rates would be beneficial. New additives and hybrid electrolytes that can chemically trap polysulfides without reducing ionic conductivity are a promising research direction. Researchers may explore fluorinated electrolytes or solid-liquid hybrid systems that can combine the benefits of solid-state electrolytes and liquid-based electrolytes.

4.3.2. Solid-state electrolytes

Future work on solid-state electrolytes can help avoid many of the issues related to polysulfide dissolution and electrolyte degradation. Research should focus on developing high-conductivity solid-state electrolytes, such as sulfide-based and oxide-based materials, that can withstand the demands of Li-S battery cycling. Moreover, integrating solid-state electrolytes with sulfur-based cathodes and lithium anodes will be crucial for improving the stability and safety of the batteries.

4.4. Anode development and interface optimization

While much of the research on Li-S batteries has focused on the cathode, the anode and interface between the anode and electrolyte also play a crucial role in performance and stability.

4.4.1. Lithium metal anodes

Li-S batteries often use lithium metal as the anode, which can suffer from dendrite formation during cycling. Future research should focus on dendrite-free lithium metal anodes and protective layers that prevent dendrite growth and improve the efficiency of lithium deposition. One promising area is the use of solid-state and lithiated polymer-based protective layers to suppress dendrite formation.

4.4.2. Interface engineering

Enhancing the interfacial stability between the lithium anode and the electrolyte is crucial for extending battery life. Research into the development of solid-electrolyte interphase (SEI) layers that are stable, conductive, and prevent polysulfide degradation could greatly enhance Li-S battery performance.

4.5. Scaling up for commercial applications

While lab-scale experiments have shown promising results, scaling up Li-S batteries for real-world applications requires breakthroughs in manufacturing techniques and cost-effective production. Future research efforts should be directed towards:

4.5.1. Low-cost and scalable manufacturing

Developing scalable and cost-effective methods to synthesize sulfur-carbon composites at large scales will be critical for commercial production. Roll-to-roll processing and other mass-production techniques should be explored to reduce production costs. Sulfur is abundant and inexpensive, but sourcing and incorporating it into battery production at an industrial scale will require new, sustainable methods of processing and integrating sulfur. Additionally, research into recycling strategies for Li-S batteries will be essential for creating a circular economy around sulfur-based energy storage technologies.

4.5.2. Cell and system integration

The integration of Li-S cells into full battery packs requires optimization of cell architecture, management systems, and thermal regulation to ensure long-term stability and performance in applications like electric vehicles and grid storage. Large-scale real-world testing, particularly in electric vehicles and renewable energy storage, will provide valuable insights into the long-term stability and economic viability of Li-S batteries. Research should focus on real-world durability testing, including the effects of high temperatures, varying charge/discharge rates, and other environmental factors on battery life.

4.6. Safety and sustainability

The safety and environmental sustainability of Li-S batteries will be critical for their widespread adoption.

4.6.1. Safety enhancements

Researchers are working on creating non-flammable, safe electrolytes that reduce the risk of thermal runaway and fires. The development of solid-state batteries will also address many safety concerns associated with liquid electrolytes, such as leakage and flammability.

4.6.2. Environmental sustainability

Li-S batteries rely on sulfur, a material that is abundant and cost-effective, but future research should also focus on ensuring that the extraction and use of sulfur are done in an environmentally responsible manner. Additionally, exploring recycling methods for sulfur and other battery components will be important to minimize waste and improve the sustainability of Li-S technology.

Thus, future research on Lithium-Sulfur (Li-S) batteries will focus on overcoming the key challenges related to cycle life, electrical conductivity, electrolyte stability, and anode development. In addition, scalability, cost-effectiveness, safety, and environmental sustainability will be critical for the practical application of Li-S technology in industries like electric vehicles, grid storage, and consumer electronics. As research continues to address these obstacles, Li-S batteries are poised to become a game-changer in energy storage, offering higher energy densities, lower costs, and a more sustainable future for energy storage technologies.

5. Conclusion

Lithium-Sulfur (Li-S) batteries hold tremendous promise for revolutionizing energy storage, particularly in applications such as electric vehicles (EVs), grid storage, and consumer electronics, due to their exceptional theoretical energy density, cost-effectiveness, and environmental sustainability. Despite their potential, the widespread adoption of Li-S batteries has been hampered by significant challenges, including low cycle life, poor electrical conductivity, electrolyte instability, and the difficulty of scaling up for commercial production. Recent advances in Li-S battery research have made substantial progress toward addressing these issues. Innovations in polysulfide trapping, sulfur-carbon composites, solid-state electrolytes, and nanostructured cathodes have shown promise in improving cycle stability, conductivity, and overall battery performance. Furthermore, the development of solid-state and ionic liquid electrolytes, advanced lithium metal anodes, and protective layers is paving the way for safer, more durable, and efficient Li-S batteries.

However, challenges remain in ensuring the scalability of these technologies, reducing production costs, and ensuring long-term performance under real-world conditions. Research efforts must continue to focus on improving the cycle life, optimizing battery systems for large-scale manufacturing, and addressing issues related to safety, recycling, and sustainability. With ongoing research and development, Li-S batteries are poised to offer a promising alternative to current energy storage solutions, contributing to a more sustainable and efficient energy future. If these technological barriers can be overcome, Li-S batteries will likely play a critical role in powering a range of applications, from electric vehicles to renewable energy storage systems, ultimately helping to reduce global reliance on fossil fuels and move toward a greener future.

Author contributions: Conceptualization, MMA and RS; methodology, JM; software, MD; validation, MMA, JM and JP; formal analysis, MRU; investigation, MRU; resources, JM; data curation, JM; writing—original draft preparation, MMA; writing—review and editing, RS; visualization, MD; supervision, MMA. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Gao Y, Pan Z, Sun J, et al. High-Energy Batteries: Beyond Lithium-Ion and Their Long Road to Commercialisation. Nano-Micro Letters. 2022; 14(1). doi: 10.1007/s40820-022-00844-2
2. Xu J, Cai X, Cai S, et al. High-Energy Lithium-Ion Batteries: Recent Progress and a Promising Future in Applications. Energy & Environmental Materials. 2023; 6(5). doi: 10.1002/eem2.12450
3. Feng Y, Wang G, Ju J, et al. Towards high energy density Li–S batteries with high sulfur loading: From key issues to advanced strategies. Energy Storage Materials. 2020; 32: 320-355. doi: 10.1016/j.ensm.2020.06.043
4. Raza H, Bai S, Cheng J, et al. Li-S Batteries: Challenges, Achievements and Opportunities. Electrochemical Energy Reviews. 2023; 6(1). doi: 10.1007/s41918-023-00188-4

5. Ryu J, Song W, Lee S, et al. A Game Changer: Functional Nano/Micromaterials for Smart Rechargeable Batteries. Advanced Functional Materials. 2019; 30(2). doi: 10.1002/adfm.201902499
6. Yang Z, Huang H, Lin F. Sustainable Electric Vehicle Batteries for a Sustainable World: Perspectives on Battery Cathodes, Environment, Supply Chain, Manufacturing, Life Cycle, and Policy. Advanced Energy Materials. 2022; 12(26). doi: 10.1002/aenm.202200383
7. Yang C, Li P, Yu J, et al. Approaching energy-dense and cost-effective lithium–sulfur batteries: From materials chemistry and price considerations. Energy. 2020; 201: 117718. doi: 10.1016/j.energy.2020.117718
8. Zhou G, Chen H, & Cui Y. Formulating energy density for designing practical lithium–sulfur batteries. Nature Energy. 2022; 7: 312–319. doi: 10.1038/s41560-022-01001-0
9. Zhong M, Guan J, Sun J, et al. A Cost- and Energy Density-Competitive Lithium-Sulfur Battery. Energy Storage Materials. 2021; 41: 588-598. doi: 10.1016/j.ensm.2021.06.037
10. Liang Z, Shen J, Xu X, et al. Advances in the Development of Single-Atom Catalysts for High-Energy-Density Lithium–Sulfur Batteries. Advanced Materials. 2022; 34(30). doi: 10.1002/adma.202200102
11. Wu X, Ji G, Wang J, et al. Toward Sustainable All Solid-State Li–Metal Batteries: Perspectives on Battery Technology and Recycling Processes. Advanced Materials. 2023; 35(51). doi: 10.1002/adma.202301540
12. Fang R, Zhao S, Sun Z, et al. More Reliable Lithium-Sulfur Batteries: Status, Solutions and Prospects. Advanced Materials. 2017; 29(48). doi: 10.1002/adma.201606823
13. Zhao C, Amine K, Xu GL. Nontraditional Approaches To Enable High-Energy and Long-Life Lithium–Sulfur Batteries. Accounts of Chemical Research. 2023; 56(19): 2700-2712. doi: 10.1021/acs.accounts.3c00400
14. Liu Y, Liu S, Li G, et al. Strategy of Enhancing the Volumetric Energy Density for Lithium–Sulfur Batteries. Advanced Materials. 2020; 33(8). doi: 10.1002/adma.202003955
15. Li S, Wang K, Zhang G, et al. Fast Charging Anode Materials for Lithium-Ion Batteries: Current Status and Perspectives. Advanced Functional Materials. 2022; 32(23). doi: 10.1002/adfm.202200796
16. Wang Y, Lai W, Chou S, et al. Remedies for Polysulfide Dissolution in Room-Temperature Sodium–Sulfur Batteries. Advanced Materials. 2020; 32(18). doi: 10.1002/adma.201903952
17. Huang Y, Lin L, Zhang C, et al. Recent Advances and Strategies toward Polysulfides Shuttle Inhibition for High-Performance Li–S Batteries. Advanced Science. 2022; 9(12): 2106004. doi: 10.1002/advs.202106004
18. Pan H, Cheng Z, He P, Zhou H. A Review of Solid-State Lithium–Sulfur Battery: Ion Transport and Polysulfide Chemistry. Energy Fuels. 2020; 34(10): 11942–11961. doi: 10.1021/acs.energyfuels.0c02647
19. Geng H, Peng Y, Qu L, et al. Structure Design and Composition Engineering of Carbon-Based Nanomaterials for Lithium Energy Storage. Advanced Energy Materials. 2020; 10(10). doi: 10.1002/aenm.201903030
20. Huang L, Li J, Liu B, et al. Electrode Design for Lithium–Sulfur Batteries: Problems and Solutions. Advanced Functional Materials. 2020; 30(22): 1910375. doi: 10.1002/adfm.201910375
21. Chen L, Yu H, Li W, et al. Interlayer design based on carbon materials for lithium–sulfur batteries: a review. Journal of Materials Chemistry A. 2020; 8(21): 10709-10735. doi: 10.1039/d0ta03028g
22. Pan H, Cheng Z, Zhou Z, et al. Boosting Lean Electrolyte Lithium–Sulfur Battery Performance with Transition Metals: A Comprehensive Review. Nano-Micro Letters. 2023; 15(1). doi: 10.1007/s40820-023-01137-y
23. Liang Y, Liu H, Wang G, et al. Challenges, interface engineering, and processing strategies toward practical sulfide-based all-solid-state lithium batteries. InfoMat. 2022; 4(5). doi: 10.1002/inf2.12292
24. Eng AYS, Kumar V, Zhang Y, et al. Room-Temperature Sodium–Sulfur Batteries and Beyond: Realizing Practical High Energy Systems through Anode, Cathode, and Electrolyte Engineering. Advanced Energy Materials. 2021; 11(14). doi: 10.1002/aenm.202003493
25. Du L, Wu R, Wu Z, et al. Research progress of all-solid-state lithium–sulfur batteries with sulfide solid electrolytes: materials, interfaces, challenges, and prospects. Materials Chemistry Frontiers. 2023; 7(22): 5760-5785. doi: 10.1039/D3QM00607G
26. Bandyopadhyay S, Nandan B. A review on design of cathode, anode and solid electrolyte for true all-solid-state lithium sulfur batteries. Materials Today Energy. 2022; 31: 101201. doi: 10.1016/j.mtener.2022.101201
27. Nanda S, Manthiram A. Lithium degradation in lithium–sulfur batteries: insights into inventory depletion and interphasial evolution with cycling. Energy & Environmental Science. 2020; 13(8): 2501-2514. doi: 10.1039/d0ee01074j

28. Wen G, Rehman S, Tranter TG, et al. Insights into Multiphase Reactions during Self-Discharge of Li-S Batteries. Chemistry of Materials. 2020; 32(11): 4518-4526. doi: 10.1021/acs.chemmater.0c00235
29. de Vasconcelos LS, Xu R, Xu Z, et al. Chemomechanics of Rechargeable Batteries: Status, Theories, and Perspectives. Chemical Reviews. 2022; 122(15): 13043-13107. doi: 10.1021/acs.chemrev.2c00002
30. Shaibani M, Mirshekarloo MS, Singh R, et al. Expansion-tolerant architectures for stable cycling of ultrahigh-loading sulfur cathodes in lithium-sulfur batteries. Science Advances. 2020; 6(1). doi: 10.1126/sciadv.aay2757
31. Tiwari S, Yadav V, Poonia AK, et al. Exploring advances in sulfur composite cathodes for lithium-sulfur batteries: A comprehensive review. Journal of Energy Storage. 2024; 94: 112347. doi: 10.1016/j.est.2024.112347
32. Han J, Li H, Kong D, et al. Realizing High Volumetric Lithium Storage by Compact and Mechanically Stable Anode Designs. ACS Energy Letters. 2020; 5(6): 1986-1995. doi: 10.1021/acsenergylett.0c00851
33. Tan J, Matz J, Dong P, et al. Appreciating the role of polysulfides in lithium-sulfur batteries and regulation strategies by electrolytes engineering. Energy Storage Materials. 2021; 42: 645-678. doi: 10.1016/J.ENSM.2021.08.012
34. Sang P, Chen Q, Wang DY, et al. Organosulfur Materials for Rechargeable Batteries: Structure, Mechanism, and Application. Chemical Reviews. 2023; 123(4): 1262-1326. doi: 10.1021/acs.chemrev.2c00739
35. Suzanowicz A, Mei C, Mandal B. Approaches to Combat the Polysulfide Shuttle Phenomenon in Li–S Battery Technology. Batteries. 2022; 8(5): 45. doi: 10.3390/batteries8050045
36. Yan R, Ma T, Cheng M, et al. Metal–Organic-Framework-Derived Nanostructures as Multifaceted Electrodes in Metal–Sulfur Batteries. Advanced Materials. 2021; 33(27). doi: 10.1002/adma.202008784
37. Cheng M, Yan R, Yang Z, et al. Polysulfide Catalytic Materials for Fast-Kinetic Metal–Sulfur Batteries: Principles and Active Centers. Advanced Science. 2021; 9(2). doi: 10.1002/advs.202102217
38. Zheng ZJ, Ye H, Guo ZP. Recent progress on pristine metal/covalent-organic frameworks and their composites for lithium–sulfur batteries. Energy & Environmental Science. 2021; 14(4): 1835-1853. doi: 10.1039/d0ee03181j
39. Wu J, Liu S, Han F, et al. Lithium/Sulfide All-Solid-State Batteries using Sulfide Electrolytes. Advanced Materials. 2020; 33(6). doi: 10.1002/adma.202000751
40. Wang C, Liang J, Zhao Y, et al. All-solid-state lithium batteries enabled by sulfide electrolytes: from fundamental research to practical engineering design. Energy & Environmental Science. 2021; 14(5): 2577-2619. doi: 10.1039/d1ee00551k
41. Kim KJ, Balaish M, Wadaguchi M, et al. Solid-State Li–Metal Batteries: Challenges and Horizons of Oxide and Sulfide Solid Electrolytes and Their Interfaces. Advanced Energy Materials. 2020; 11(1). doi: 10.1002/aenm.202002689
42. Yang L, Li H, Li Q, et al. Research Progress on Improving the Sulfur Conversion Efficiency on the Sulfur Cathode Side in Lithium–Sulfur Batteries. Industrial & Engineering Chemistry Research. 2020; 59(48): 20979-21000. doi: 10.1021/acs.iecr.0c04960
43. Yang L, Li Q, Wang Y, et al. A review of cathode materials in lithium-sulfur batteries. Ionics. 2020; 26: 5299–5318. doi: 10.1007/s11581-020-03767-3
44. Zhang Q, Huang Q, Hao S, et al. Polymers in Lithium–Sulfur Batteries. Advanced Science. 2021; 9(2). doi: 10.1002/advs.202103798
45. Zhang M, Chen W, Xue L, et al. Adsorption-Catalysis Design in the Lithium-Sulfur Battery. Advanced Energy Materials. 2020; 10(2): 1903008. doi: 10.1002/aenm.201903008
46. Zeng L, Zhu J, Chu PK, et al. Catalytic Effects of Electrodes and Electrolytes in Metal–Sulfur Batteries: Progress and Prospective. Advanced Materials. 2022; 34(49): 2204636. doi: 10.1002/adma.202204636
47. Jeoun Y, Kim MS, Lee SH, et al. Lean-electrolyte lithium-sulfur batteries: Recent advances in the design of cell components. Chemical Engineering Journal. 2022; 450: 138209. doi: 10.1016/j.cej.2022.138209
48. Yang T, Xia J, Piao Z, et al. Graphene-Based Materials for Flexible Lithium–Sulfur Batteries. ACS Nano. 2021; 15(9): 13901–13923. doi: 10.1021/acsnano.1c03183
49. Xiao Q, Yang J, Wang X, et al. Carbon-based flexible self-supporting cathode for lithium-sulfur batteries: Progress and perspective. Carbon Energy. 2021; 3(2): 271-302. doi: 10.1002/cey2.96
50. Zhang Z, Kong L, Liu S, et al. A High-Efficiency Sulfur/Carbon Composite Based on 3D Graphene Nanosheet@Carbon Nanotube Matrix as Cathode for Lithium–Sulfur Battery. Advanced Energy Materials. 2017; 7(11). doi: 10.1002/aenm.201602543
51. Li Z, Huang Y, Yuan L, et al. Status and prospects in sulfur–carbon composites as cathode materials for rechargeable lithium–sulfur batteries. Carbon. 2015; 92: 41-63. doi: 10.1016/j.carbon.2015.03.008

52. Park JH, Choi WY, Yang J, et al. Nitrogen-rich hierarchical porous carbon paper for a free-standing cathode of lithium sulfur battery. Carbon. 2021; 172: 624-636. doi: 10.1016/j.carbon.2020.10.078
53. Tomer VK, Malik R, Tjong J, Sain M. State and future implementation perspectives of porous carbon-based hybridized matrices for lithium sulfur battery. Coordination Chemistry Reviews. 2023; 481: 215055. doi: 10.1016/j.ccr.2023.215055
54. Liu J, Zhou Y, Yan T, et al. Perspectives of High-Performance Li–S Battery Electrolytes. Advanced Functional Materials. 2023: 34(4): 2309625. doi: 10.1002/adfm.202309625
55. Zhao M, Li BQ, Peng HJ, et al. Lithium–Sulfur Batteries under Lean Electrolyte Conditions: Challenges and Opportunities. Angewandte Chemie International Edition. 2020; 59(31): 12636-12652. doi: 10.1002/anie.201909339
56. Li S, Zhang W, Zheng J, et al. Inhibition of Polysulfide Shuttles in Li–S Batteries: Modified Separators and Solid-State Electrolytes. Advanced Energy Materials. 2021; 11(2): 2000779. doi: 10.1002/aenm.202000779
57. Dorai A, Kawamura J, & Omata T. Visualization of polysulfide dissolution in lithium-sulfur batteries using in-situ NMR microimaging. Electrochemistry Communications. 2022; 141: 107360. doi: 10.1016/j.elecom.2022.107360
58. Lin Y, Huang S, Zhong L, et al. Organic liquid electrolytes in Li-S batteries: actualities and perspectives. Energy Storage Materials. 2021; 34: 128-147. doi: 10.1016/J.ENSM.2020.09.009
59. Chen S, Zhang M, Zou P, et al. Historical development and novel concepts on electrolytes for aqueous rechargeable batteri es. Energy & Environmental Science. 2022; 15(5): 1805-1839. doi: 10.1039/D2EE00004K
60. Baloch M, Vizintin A, Chellappan RK, et al. Application of Gel Polymer Electrolytes Based on Ionic Liquids in Lithium-Sulfur Batteries. Journal of The Electrochemical Society. 2016; 163(10): A2390-A2398. doi: 10.1149/2.1151610jes
61. Jin J, Wen Z, Liang X, et al. Gel polymer electrolyte with ionic liquid for high performance lithium sulfur battery. Solid State Ionics. 2012; 225: 604-607. doi: 10.1016/j.ssi.2012.03.012
62. Ding B, Wang J, Fan Z, et al. Solid-state lithium–sulfur batteries: Advances, challenges and perspectives. Materials Today. 2020; 40: 114-131. doi: 10.1016/j.mattod.2020.05.020
63. Wu F, Zhang K, Liu Y, et al. Polymer electrolytes and interfaces toward solid-state batteries: Recent advances and prospects. Energy Storage Materials. 2020; 33: 26-54. doi: 10.1016/j.ensm.2020.08.002
64. Tan DHS, Wu EA, Nguyen H, et al. Elucidating Reversible Electrochemical Redox of Li6PS5Cl Solid Electrolyte. ACS Energy Letters. 2019; 4(10): 2418-2427. doi: 10.1021/acsenergylett.9b01693
65. Wang J, Wang H, Jia S, et al. Recent advances in inhibiting shuttle effect of polysulfide in lithium-sulfur batteries. Journal of Energy Storage. 2023; 72: 108372. doi: 10.1016/j.est.2023.108372
66. Suriyakumar S, Stephan AM. Mitigation of Polysulfide Shuttling by Interlayer/Permselective Separators in Lithium–Sulfur Batteries. ACS Applied Energy Materials. 2020; 3(9): 8095-8129. doi: 10.1021/acsaem.0c01354
67. Sun J, Zhang K, Fu Y, et al. Benzoselenol as an organic electrolyte additive in Li-S battery. Nano Research. 2022; 16(3): 3814-3822. doi: 10.1007/s12274-022-4361-z
68. Kim S, Kwon YM, Cho KY, et al. Metal iodides (LiI, MgI2, AlI3, TiI4, and SnI4) potentiality as electrolyte additives for Li−S batteries. Electrochimica Acta. 2021; 391: 138927. doi: 10.1016/j.electacta.2021.138927
69. Lian J, Guo W, Fu Y. Isomeric Organodithiol Additives for Improving Interfacial Chemistry in Rechargeable Li–S Batteries. Journal of the American Chemical Society. 2021; 143(29): 11063-11071. doi: 10.1021/jacs.1c04222
70. Han Z, Li S, Wu Y, et al. Challenges and key parameters in exploring the cyclability limitation of practical lithium–sulfur batteries. Journal of Materials Chemistry A. 2021; 9(43): 24215-24240. doi: 10.1039/d1ta06499a
71. Li J, Niu Z, Guo C, et al. Catalyzing the polysulfide conversion for promoting lithium sulfur battery performances: A review. Journal of Energy Chemistry. 2021; 54: 434-451. doi: 10.1016/j.jechem.2020.06.009
72. Zhou L, Danilov DL, Eichel R, et al. Host Materials Anchoring Polysulfides in Li–S Batteries Reviewed. Advanced Energy Materials. 2020; 11(15). doi: 10.1002/aenm.202001304
73. Gong X, Song Y, Zhao N, et al. Mofs hybridized carbon matrix as multi-functional cathodic interlayer for lithium-sulfur batteries. Coordination Chemistry Reviews. 2024; 512: 215877. doi: 10.1016/j.ccr.2024.215877
74. Wang F, Han Y, Feng X, et al. Mesoporous Carbon-Based Materials for Enhancing the Performance of Lithium-Sulfur Batteries. International Journal of Molecular Sciences. 2023; 24(8): 7291. doi: 10.3390/ijms24087291
75. Kwon Y, Choi YS, Wang Q, et al. Clarifying the Role of Ordered Mesoporous Carbon on a Separator for High-Performance Lithium–Sulfur Batteries. ACS Applied Energy Materials. 2023; 6(19): 9975-9984. doi: 10.1021/acsaem.3c01523
76. Cai G, Yan P, Zhang L, et al. Metal–Organic Framework-Based Hierarchically Porous Materials: Synthesis and Applications. Chemical Reviews. 2021; 121(20): 12278-12326. doi: 10.1021/acs.chemrev.1c00243

77. Kang X, Di Bernardo I, Yang H, et al. Metal–organic framework microdomains in 3D conductive host as polysulfide inhibitor for fast, long-cycle Li–S batteries. Applied Surface Science. 2021; 535: 147680. doi: 10.1016/j.apsusc.2020.147680
78. Duan Y, Bai X, Yu T, et al. Research progress and prospect in typical sulfide solid-state electrolytes. Journal of Energy Storage. 2022; 55: 105382. doi: 10.1016/j.est.2022.105382
79. Wang JC, Zhao LL, Zhang N, et al. Interfacial stability between sulfide solid electrolytes and lithium anodes: Challenges, strategies and perspectives. Nano Energy. 2024; 123: 109361. doi: 10.1016/j.nanoen.2024.109361
80. Jaumaux P, Wu J, Shanmukaraj D, et al. Non-Flammable Liquid and Quasi-Solid Electrolytes toward Highly-Safe Alkali Metal-Based Batteries. Advanced Functional Materials. 2020; 31(10). doi: 10.1002/adfm.202008644
81. Wang H, Sheng L, Yasin G, et al. Reviewing the current status and development of polymer electrolytes for solid-state lithium batteries. Energy Storage Materials. 2020; 33: 188-215. doi: 10.1016/j.ensm.2020.08.014
82. Liu G, Sun Q, Li Q, et al. Electrolyte Issues in Lithium–Sulfur Batteries: Development, Prospect, and Challenges. Energy & Fuels. 2021; 35(13): 10405-10427. doi: 10.1021/acs.energyfuels.1c00990
83. Hong X, Wang R, Liu Y, et al. Recent advances in chemical adsorption and catalytic conversion materials for Li–S batteries. Journal of Energy Chemistry. 2020; 42: 144-168. doi: 10.1016/j.jechem.2019.07.001
84. Zhang T, Ma C, Wang R, et al. Electrocatalysts composed of amorphous red phosphorous nanosheets coupled with carboxylic group carbon nanotubes for Li-S batteries. Journal of Energy Storage. 2024; 77: 109916. doi: 10.1016/j.est.2023.109916
85. Zhao F, Xue J, Shao W, et al. Toward high-sulfur-content, high-performance lithium-sulfur batteries: Review of materials and technologies. Journal of Energy Chemistry. 2023; 80: 625-657. doi: 10.1016/j.jechem.2023.02.009
86. Zhang J, Dong Z, Wang X, et al. Sulfur nanocrystals anchored graphene composite with highly improved electrochemical performance for lithium–sulfur batteries. Journal of Power Sources. 2014; 270: 1-8. doi: 10.1016/j.jpowsour.2014.07.089
87. Wei P, Fan M, Chen H, et al. High-capacity graphene/sulfur/polyaniline ternary composite cathodes with stable cycling performance. Electrochimica Acta. 2015; 174: 963-969. doi: 10.1016/j.electacta.2015.06.052
88. Tomer VK, Malik R, Tjong J, et al. Recent advances in plant-derived porous carbon for lithium–sulfur batteries. Journal of Energy Storage. 2024; 99: 113186. doi: 10.1016/j.est.2024.113186
89. Bora M, Bhattacharjya D, Saikia BK, et al. Coal-Derived Activated Carbon for Electrochemical Energy Storage: Status on Supercapacitor, Li-Ion Battery, and Li–S Battery Applications. Energy & Fuels. 2021; 35(22): 18285-18307. doi: 10.1021/acs.energyfuels.1c02518
90. Haruna A, Dönmez KB, Hooshmand S, et al. armony of nanosystems: Graphitic carbon nitride/carbon nanomaterial hybrid architectures for energy storage in supercapacitors and batteries. Carbon. 2024; 226: 119177. doi: 10.1016/j.carbon.2024.119177
91. Khodabakhshi S, Fulvio PF, Andreoli E. Carbon black reborn: Structure and chemistry for renewable energy harnessing. Carbon. 2020; 162: 604-649. doi: 10.1016/j.carbon.2020.02.058
92. Hong X, Liu Y, Li Y, et al. Application Progress of Polyaniline, Polypyrrole and Polythiophene in Lithium-Sulfur Batteries. Polymers. 2020; 12(2): 331. doi: 10.3390/polym12020331
93. Goyal M, Singh K, Bhatnagar N. Conductive polymers: A multipurpose material for protecting coating. Progress in Organic Coatings. 2024; 187: 108083. doi: 10.1016/j.porgcoat.2023.108083
94. Zheng J, Gu M, Chen H, et al. Ionic liquid-enhanced solid state electrolyte interface (SEI) for lithium–sulfur batteries. Journal of Materials Chemistry A. 2013; 1(29): 8464. doi: 10.1039/c3ta11553d
95. Pal U, Girard GMA, O'Dell LA, et al. Improved Li-Ion Transport by DME Chelation in a Novel Ionic Liquid-Based Hybrid Electrolyte for Li–S Battery Application. The Journal of Physical Chemistry C. 2018; 122(26): 14373-14382. doi: 10.1021/acs.jpcc.8b03909
96. Qian J, Jin B, Li Y, et al. Research progress on gel polymer electrolytes for lithium-sulfur batteries. Journal of Energy Chemistry. 2021; 56: 420-437. doi: 10.1016/j.jechem.2020.08.026
97. Yang Q, Deng N, Chen J, et al. The recent research progress and prospect of gel polymer electrolytes in lithium-sulfur batteries. Chemical Engineering Journal. 2021; 413: 127427. doi: 10.1016/j.cej.2020.127427
98. Hwang JY, Park H, Kim H, et al. Advanced Cathodes for Practical Lithium–Sulfur Batteries. Accounts of Materials Research. 2025; 6(2): 245–258. doi: 10.1021/accountsmr.4c00368
99. Shi C, Yu M. Flexible solid-state lithium-sulfur batteries based on structural designs. Energy Storage Materials. 2023; 57: 429-459. doi: 10.1016/j.ensm.2023.02.031

100. Gao G, Yang X, Bi J, et al. Advanced engineering strategies for Li2S cathodes in lithium–sulfur batteries. Journal of Materials Chemistry A. 2023; 11(48): 26318-26339. doi: 10.1039/d3ta06057h
101. Zhou G, Xu L, Hu G, et al. Nanowires for Electrochemical Energy Storage. Chemical Reviews. 2019; 119(20): 11042-11109. doi: 10.1021/acs.chemrev.9b00326
102. Liu K, Zhao H, Ye D, et al. Recent progress in organic Polymers-Composited sulfur materials as cathodes for Lithium-Sulfur battery. Chemical Engineering Journal. 2021; 417: 129309. doi: 10.1016/j.cej.2021.129309
103. Chen X, Zhao C, Yang K, et al. Conducting Polymers Meet Lithium–Sulfur Batteries: Progress, Challenges, and Perspectives. Energy & Environmental Materials. 2023; 6(5). doi: 10.1002/eem2.12483
104. Shi QX, Yang CY, Pei HJ, et al. Layer-by-layer self-assembled covalent triazine framework/electrical conductive polymer functional separator for Li-S battery. Chemical Engineering Journal. 2021; 404: 127044. doi: 10.1016/j.cej.2020.127044
105. Huang JQ, Zhang Q, Wei F. Multi-functional separator/interlayer system for high-stable lithium-sulfur batteries: Progress and prospects. Energy Storage Materials. 2015; 1: 127-145. doi: 10.1016/j.ensm.2015.09.008
106. McCreary C, An Y, Kim SU, et al. A Perspective on Li/S Battery Design: Modeling and Development Approaches. Batteries. 2021; 7(4): 82. doi: 10.3390/batteries7040082
107. Ritter TG, Pappu S, Shahbazian-Yassar R. High-Entropy Materials for Lithium Batteries. Batteries. 2024; 10(3): 96. doi: 10.3390/batteries10030096
108. Deng W, Phung J, Li G, et al. Realizing high-performance lithium-sulfur batteries via rational design and engineering strategies. Nano Energy. 2021; 82: 105761. doi: 10.1016/j.nanoen.2021.105761
109. Liu X, Fan K, Huang X, et al. Recent advances in artificial intelligence boosting materials design for electrochemical energy storage. Chemical Engineering Journal. 2024; 490: 151625. doi: 10.1016/j.cej.2024.151625