

Review

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Review

Scientometric Insights into Rechargeable Solid-State Battery Developments

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Abstract: Solid-state batteries (SSBs) offer significant improvements in safety, energy density, and cycle life over conventional lithium-ion batteries, with promising applications in electric vehicles and grid storage due to their non-flammable electrolytes and high-capacity lithium metal anodes. However, challenges such as interfacial resistance, low ionic conductivity, and manufacturing scalability hinder their commercial viability. This study conducts a comprehensive scientometric analysis, examining 131 peer-reviewed SSB research articles from IEEE Xplore and Web of Science databases to identify key thematic areas and bibliometric patterns driving SSB advancements. Through a detailed analysis of thematic keywords and publication trends, this study identifies innovations in high-ionic-conductivity solid electrolytes and advanced cathode materials, which have significantly impacted performance gains and are critical to commercializing SSB technology. The findings provide actionable insights for researchers and industry stakeholders, specifically in the areas of interfacial engineering and manufacturability, where gaps in long-term stability and scalable production continue to hinder widespread adoption of SSBs. The study reveals key advances in electrolyte interface stability and ion transport mechanisms, identifying how solid-state electrolyte modifications and cathode coating methods improve charge cycling and reduce dendrite formation, particularly for high-energy-density applications. By mapping publication growth and clustering research themes, this study highlights high-impact areas such as cycling stability and ionic conductivity, providing a roadmap for targeted research efforts and strategic investments to advance SSB technology for critical applications in transportation and storage. The insights from this analysis guide researchers toward impactful areas, such as electrolyte optimization and scalable production, and provide industry leaders with strategies for accelerating SSB commercialization to extend electric vehicle range, enhance grid storage, and improve overall energy efficiency.

Keywords: Solid-state lithium-ion battery; Electric vehicles; Ionic conductivity; Dendrite suppression; Thermal management; Cycle life; Energy density; Electrode-electrolyte interface; Performance evaluation; Battery architecture

1. Introduction

The global transition to cleaner and more sustainable transportation technologies has accelerated in response to increasingly stringent emissions regulations and environmental concerns [1]. Vehicle electrification, driven by rechargeable lithium-ion battery (LIB) technology, has emerged as the dominant solution in this shift [2]. Despite offering advantages in energy density and cost, LIBs present critical challenges, particularly regarding safety risks such as flammable electrolytes and dendrite formation [3]. These issues raise the potential for thermal runaway and short circuits under high-demand applications [4]. Solid-state batteries (SSBs), featuring non-flammable solid electrolytes and high-capacity lithium metal anodes, have emerged as promising alternatives to LIBs by addressing key challenges, such as improving safety through dendrite suppression [5] and expanding operational stability across wide temperature ranges [6]. Furthermore, SSBs enable the direct use of lithium metal as an anode, unlocking the potential for higher energy densities, which translates to longer ranges for electric vehicles, drones, and other mobility applications [7].

Nevertheless, substantial obstacles persist in SSB development, notably in achieving stable, low-resistance solid-electrolyte interfaces with electrodes, which impacts both cycle life and energy efficiency [8]. Unlike liquid electrolytes, solid-state materials cannot easily conform to electrode surfaces, making it difficult to achieve consistent, high-quality contact across the interface. Poor interface contact can lead to increased resistance, reduced ionic conductivity, poor charge cycling stability, and degraded battery performance. To overcome these hurdles, ongoing research has focused on optimizing solid electrolyte materials, improving interface design, and integrating advanced manufacturing techniques [9].

The **goal** of this study is to provide an in-depth scientometric analysis of SSB research trends, examining recent developments in key areas such as interfacial engineering, ionic conductivity, and scalable manufacturing to identify emerging innovations and persistent challenges hindering SSB commercialization. The scientometric approach examines SSB research dynamics through metrics including publication frequency, thematic keyword analysis, and citation impact across major research categories, enabling a comprehensive view of progress and gaps in SSB technology development [10]. This analysis integrates insights from experimental and theoretical studies, identifying major trends such as electrolyte stability and ion transport improvements, as well as key challenges like manufacturability, which collectively shape the direction of future SSB research and application. The study **contributes** to a deeper understanding of SSB research trajectories by mapping high-impact topics like cycling stability and interfacial engineering, offering insights that guide targeted research efforts and inform industry strategies for SSB deployment in transportation and energy sectors.

The organization of the rest of this paper is as follows: Section 2 provides a primer on rechargeable batteries by using the lithium-ion architecture as a focus, reviews the solid-state design, and active research areas. Section 3 describes the methodological workflow, including the analytical methods developed for the scientometric approach. Section 4 presents the results, including a categorization of the problem areas found within the corpus, and visualizations of the data from the analysis. Section 5 discusses the key findings from the most recent literature reviewed, limitations of the work, and future research directions. Section 6 concludes the research and suggests future work.

2. Literature Review

Subsection 2.1 introduces the operational fundamentals of LIBs as a foundation for understanding the technological advances offered by SSBs, particularly in safety, ionic conductivity, and compatibility with lithium anodes. Section 2.2 summarizes how SSB designs differ from LIBs. Section 2.3 explores the literature on active research within SSB development and battery pack development.

2.1. Rechargeable Battery Primer

LIBs have surpassed nickel metal hydride (NiMH) batteries in popularity because of their superior energy density, lightweight design, and longer cycle life, making them integral to electric vehicle and portable device applications [11]. Despite these advantages, LIBs continue to face safety risks, including fire hazards linked to mechanical, electrical, or thermal abuse [12]. These issues stem primarily from the flammability of liquid electrolyte and dendrite formation on lithium anodes. Moreover, the transportation industry is seeking higher energy density and safer batteries to increase electric vehicle (EV) driving range and to enable new transport modes such as electrified aircraft [13].

2.1.1. Basic Operation

As illustrated in Figure 1, LIBs consist of an anode and cathode separated by a polymer membrane and immersed in a liquid electrolyte, which facilitates lithium-ion transfer. The dimensions shown in the figure are typical but vary depending on the specific materials used and the design goals of the battery [14]. The desire is to make all layers as thin as possible without

compromising safety or mechanical integrity, which helps to maximize energy density and minimize internal resistance [15].

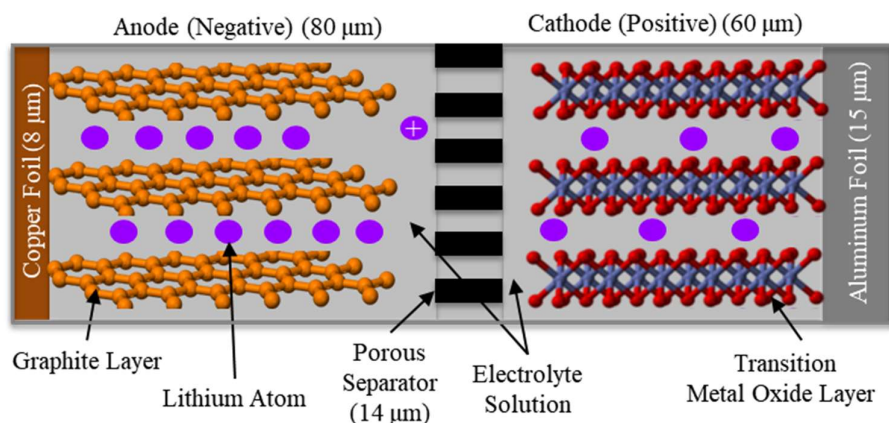


Figure 1. The typical electrochemical structure of a LIB. ©Raj Bridgelall.

The microporous polymer separator prevents the two electrodes from internally short circuiting [16]. The separator is an insulator that blocks the conduction of electrons while allowing the passage of ions through its electrolyte filled pores.

The anode material (negative electrode) is typically composed of graphite, a stable form of carbon atoms organized as a crystal [17]. The typical manufacturing process coats the anode and cathode materials onto thin copper and aluminum foils, respectively. These foils, also called current collectors, facilitate electron conduction through an external circuit. The cathode material (positive electrode) is usually a lithium metal oxide such as lithium cobalt oxide (a crystalline solid) or lithium iron phosphate (an inorganic compound) [18]. Anode and cathode materials store lithium atoms by inserting them within their layered atomic structure during the charge and discharge cycles, respectively, in a chemical process called intercalation.

Both the anode and cathode materials are porous, containing gaps of various sizes that enable the liquid electrolyte to permeate the pores [19]. Ideally, the manufacturing process seeks to distribute the electrolyte evenly throughout the porous structures. This ensures that lithium ions can reach every part of the anode and cathode materials, maximizing their utilization and enhancing the battery's overall energy density.

When charged, the anode has a higher chemical potential relative to the cathode because of the higher concentration of lithium atoms [20]. During discharge, this concentration gradient creates a chemical potential difference that drives positively charged lithium ions (Li^+) from the anode to a lower potential energy at the cathode. This works because Li^+ have a natural tendency to move toward a state of lower chemical potential energy by giving up their single outer shell electron in an oxidation reaction.

Engineers design the composition of the cathode material to be at a higher positive electric potential (voltage) relative to the anode [18]. This potential difference, typically between 3 and 4 volts, generates an electric field with its positive end at the cathode and its negative end at the anode. During discharge, the negative end at the anode repels electrons from the lithium atoms, while the positive end on the cathode attracts electrons. Hence, when connected to an external circuit, electrons flow from the anode to the cathode. Electrons in the cathode attract the positive migrating Li^+ with sufficient force to overcome the energy barriers associated with intercalation. Each electron in the cathode combines with a Li^+ to form a lithium atom that intercalates within the cathode material to form a stable structure. Although the positive end of the electric field at the cathode produces a repulsive electrostatic force on Li^+ , the stronger chemical gradient between the electrodes overcomes that force. That is, the electric field primarily affects the electron flow in the external circuit rather than significantly hindering ion migration.

During discharge, the combined chemical and electrical potential energies, also known as the electrochemical potential, drive the movement of lithium ions through the electrolyte and electrons through the external circuit [21]. Electrochemical potential refers to the energy level at which electrons exist in a material relative to a standard such as lithium metal. This electrochemical process powers devices connected to the battery as they harness the flow of electrons as electric current. As electrons flow through various components in the circuit, they lose potential energy corresponding to the voltage drop across each component. Hence, having lost energy from doing work in the circuit, electrons enter the cathode at a lower energy state. The battery discharges until it reaches a specified lower voltage threshold, at which point external circuitry prevents further discharge to protect the battery.

When charging, an external electrical charger applies direct current (DC) to the battery terminals, maintaining a higher positive voltage at the cathode relative to the anode [22]. This voltage difference generates an electric field within the battery that initiates oxidation reactions at the cathode. The electric field repels the positively charged ions in the cathode and pushes them through the electrolyte toward the anode. This movement occurs against the natural tendency of the Li^+ to move from the anode to the cathode during discharge. The electric field must be strong enough to overcome the chemical potential difference between the anode and cathode, effectively forcing Li^+ back into a higher chemical potential energy state when they reach the anode for storage. The recombination of Li^+ and electrons restores the lithium atoms within the anode material, effectively recharging the battery.

2.1.2. Anode Material

The anode in an LIB stores lithium atoms in graphite (a carbon crystal), though some designs use lithium titanate or silicon-based materials. Engineers choose graphite because it is inexpensive and abundant, conducts electricity with low resistance, and efficiently stores lithium ions [20]. Carbon is the smallest atom that can form the most covalent bonds, which is four. This characteristic enables it to form complex structures such as graphite and even DNA in living things. These bonds are strong because of the close proximity of carbon's valence shell to its protons, resulting in high structural integrity. Hence, carbon is likely to remain an important material in battery construction.

Graphite has a layered structure that allows lithium ions to reversibly intercalate between its layers of graphene sheets, without undergoing much expansion. A typical process to create the structure involves coating a slurry form of the material onto a copper foil, drying it, and then compressing it into a thin film current collector [23]. Slurry preparation typically involves grinding the graphite into a fine powder and mixing it with a binder and a solvent. Initially charging the battery introduces the lithium atoms to the graphite layers (lithiation) that holds them in place with electrostatic forces. This crystalline structure provides high capacity for lithium atom storage while maintaining structural stability over many cycles of charging and discharging. The ease of lithiation is due to graphite's low electrochemical potential difference from lithium metal of close to 0.1V.

Modern rechargeable batteries often use metals from the alkali group (Group 1 of the periodic table) because these metals have a single electron in their outermost shell, requiring little energy to release them [24]. The metal atoms from this group achieve a stable electronic configuration after releasing an electron. Hence, this ease of electron release is why alkali metals are among the most reactive elements in nature. Lithium is the smallest and lightest metal in the alkali group. Its low atomic mass contributes to maximizing the energy density of batteries [25]. Its small ionic radius allows it to easily move through electrolytes and insert itself into the cathode material structure. Ease of ionic movement translates to higher power output and faster charging speeds. For these reasons, it is highly likely that lithium will continue to dominate in modern battery technologies.

2.1.3. Cathode Material

The cathode material must efficiently store lithium atoms as well as create a significant electrochemical potential difference with the anode. Manufacturers select cathode materials based on their standard electrode potentials [11]. That is, a compound with a higher positive potential is better

at attracting electrons (undergoing reduction), while those with lower or negative potentials are better at losing electrons (undergoing oxidation). For example, lithium cobalt oxide (LiCoO_2), a common cathode material, creates a higher electrical potential than the anode due to its high reduction potential, the stability of its layered structure that holds lithium atoms at high energy states, and the strong tendency of cobalt to reduce when intercalating lithium atoms. These properties result in a significant voltage difference between the cathode and the anode, which is the source of the battery's energy density.

A common method for synthesizing cathode materials is a solid-state reaction. This process involves mixing lithium salts (such as lithium carbonate, Li_2CO_3) with transition metal oxides or precursors (such as cobalt oxide, iron phosphate, or manganese oxide) in a specific stoichiometric ratio [26]. Heating the mixture at high temperatures (usually 700°C – 900°C) facilitates a chemical reaction that forms the desired intercalation compound such as lithium metal oxide. Hence, the compound contains lithium atoms within its crystal structure, ready to participate in electrochemical reactions.

The cathode material determines many of the battery's characteristics, including energy density, power capability, and overall performance. Other common cathode materials include lithium iron phosphate (LiFePO_4) or LFP, lithium manganese oxide (LiMn_2O_4) or LMO, and various combinations of nickel, manganese, and cobalt (NMC), lithium nickel cobalt aluminum oxide (NCA), and lithium-titanate (LTO) [18]. Each material offers different trade-offs between energy density, power output, safety, cost, and cycle life. For example, LiCoO_2 provides high energy density but is expensive compared with alternatives and has safety concerns at high temperatures. LiFePO_4 , on the other hand, is cobalt-free, offers excellent thermal stability and long cycle life but at the cost of lower energy density. The choice of cathode material often depends on the specific application requirements, such as high energy density for mobile devices or improved safety for electric vehicles.

2.1.4. Electrolyte Material

This section discusses conventional liquid electrolytes for context to later contrast it with solid electrolytes in the next subsection. Both types of electrolytes should have a wide electrochemical stability window, meaning it should not break down at the operating voltages of the battery. However, a primary issue with liquid electrolytes is that they can decompose at elevated temperatures and ignite [27]. The liquid electrolyte in a commercial LIB is composed of a lithium salt dissolved in an organic solvent [28]. The most commonly used lithium salt is lithium hexafluorophosphate (LiPF_6). Typical organic solvents include mixtures of ethylene carbonate (EC), dimethyl carbonate (DMC), diethyl carbonate (DEC), and ethyl methyl carbonate (EMC).

The solvent contains a salt of lithium. The solvent pulls the salt apart as it dissolves to form a mixture of positive and negative ions. Each solvent molecule exhibits a polarization due to the uneven distribution of electrons within it such that one end has a positive charge with respect to the other end. Li^+ will attract the negative (or partially negative) end of a solvent molecule, surrounding it to form solvation shells. The size and structure of these shells can significantly affect the ion's mobility and, consequently, the electrolyte's conductivity. These shells lower the free energy of the system by stabilizing the ions. Therefore, manufacturers must balance the ionic conductivity and stability by carefully controlling the lithium salt concentration [26]. The solvent maintains a balanced charge of positive and negative ions. During charging, releasing a positive lithium ion into the electrolyte solution means that it must give up a positive lithium ion elsewhere in the solution to maintain a balanced charge. The system achieves this balance as electrons entering the anode combine with a positive lithium ion, pulling it from the salt solution.

When first charged in the factory, an additive to the salt solvent enables a reaction at the anode interface to form a solid protective film, called a solid electrolyte interface (SEI), on the graphite particles [29]. These reactions use from 5% to 10% of the lithium in the battery in the first charge cycle. This film is a stable surface that extends battery life. Lithium ions can pass through the SEI.

2.2. Solid State Designs

Despite their anticipated benefits relative to conventional LIBs, SSBs face numerous challenges [20]. SSB designs replace the flammable liquid electrolyte with a non-flammable or less-flammable solid electrolyte to increase safety [30]. Engineers keep lithium metal in the anode because of its high theoretical capacity and low electrochemical potential. SSBs enable the direct use of lithium metal anodes without graphite, boosting energy density. However, this requires a solid electrolyte with high ionic conductivity and chemical compatibility, a key focus area in current SSB research and development. During charging, lithium ions participate in a reduction reaction by gaining electrons from the external circuit, and the atoms deposit onto the lithium metal surface in the anode. Hence, the anode increases in mass and thickness as lithium atoms plate the lithium metal. These repeated volume changes induce mechanical stress within the anode. Over time, this stress can cause the formation of cracks or voids, which can degrade the battery's performance and life span [31].

A common issue with lithium metal is dendrite formation from the repeated shuffling of lithium ions between the electrodes during charge-discharge cycles [32]. Dendrites are needle-like structures that can grow through an electrolyte during charging. Dendrites can pierce the electrolyte and cause short circuits, leading to safety risks such as thermal runaway. Solid electrolytes replace the electrode separator and also resist dendrite growth better than liquid electrolytes [33]. However, the challenge remains significant because uneven lithium deposition during charging can exacerbate dendrite growth.

The materials used for the cathode are similar to those used in liquid-electrolyte batteries, but they must be compatible with the solid electrolyte. The anode and cathode materials form a continuous direct interface with the solid electrolyte. These interfaces must be stable to prevent side reactions that could degrade the battery's performance. The manufacturing process typically presses, sinters, or otherwise brings the solid electrolyte into intimate contact with the electrode materials [34]. This direct physical contact is essential for enabling lithium-ion transport between the electrodes. A poor contact can lead to high interfacial resistance that reduces the battery's performance.

The solid electrolyte must be highly conductive to lithium ions while remaining electronically insulating to prevent short-circuiting between the anode and cathode. Lithium ions move through the solid electrolyte via diffusion mechanisms, which is different from the free flow of stabilized solvation shells in a liquid electrolyte [35]. The diffusion of ions in a solid material involves hopping between specific sites within the crystal structure of the solid material. This can reduce the ion conductivity relative to liquid electrolytes. Engineers form these sites by promoting defects or vacancies in the lattice of the solid electrolyte. Improving the ion conductivity in solid electrolytes is an active area of research.

2.3. Active Research Areas

Current LIB material choices are the result of decades of research and development, balancing performance, safety, cost, and manufacturability [36]. Ongoing research continues to explore new materials and combinations to further improve battery performance and address current limitations. Current SSB research prioritizes enhancements in energy density, ionic conductivity, interfacial resistance, and manufacturability to support practical applications, particularly in high-demand fields like electric vehicles and grid storage.

2.3.1. Electrolyte

Solid-state electrolytes promise to be a safer alternative to flammable liquid electrolytes [27]. Solid electrolytes use a crystalline structure to create low energy pathways for ions to move under the influence of the electric field. Manufacturers can make solid electrolytes from ceramics, polymers, or glassy materials that conduct lithium ions [33]. Ceramics have high ion conductivity, but they are brittle. Polymers are more flexible, but they have lower conductivity [37]. Glassy materials have high conductivity, but they are reactive with moisture. Research seeks to develop solid electrolytes with optimal ionic conductivity, mechanical durability, and chemical stability to replace liquid electrolytes, thus enabling safer, high-performance SSBs.

2.3.2. Anode

While commonly used in LIBs, graphite's lithium storage capacity is lower than emerging materials like silicon or lithium metal, which offer higher theoretical capacities but present challenges in volume expansion and cycling stability in SSBs [38]. In particular, silicon can theoretically store up to 4.4 lithium ions per silicon atom, compared with only 1 lithium per 6 carbon atoms in traditional graphite anodes [20]. As a result, the theoretical capacity of silicon is about 4,200 mAh/g, which is more than an order of magnitude higher than that of graphite, which has a theoretical capacity of 372 mAh/g. However, the volume expansion of silicon anodes can reach 300% when absorbing lithium ions during charging, which can lead to mechanical degradation and capacity fade. Silicon anodes can also form an unstable SEI layer, especially in solid-state systems, leading to increased resistance and reduced cycle life [29].

The repeated plating and stripping of lithium atoms can roughen the surface and increase the interfacial resistance with the solid electrolyte [39]. The incomplete stripping of lithium during discharge can lead to the formation of voids that can accumulate and disrupt the structural integrity of the anode, reducing its effective capacity. Hence, researchers are investigating ways to improve the performance and longevity of lithium metal anodes through surface coatings, pre-lithiation, and microstructure 3D architectures. Applying protective coatings to the lithium metal surface can help manage the interface with the solid electrolyte and reduce the risk of dendrite formation and excessive interphase layer growth. Pre-lithiation can stabilize the lithium metal anode and reduce the initial formation of the interphase layer, leading to better cycling stability. Designing lithium metal anodes with engineered microstructures, such as 3D architectures, can accommodate volume changes more effectively and suppress dendrite formation.

2.3.3. Cathode

Increasing the voltage difference relative to the anode, while retaining the energy storage capacity, increases the battery's energy storage and delivery capability [40]. Key SSB research focuses on cathode materials capable of storing greater lithium content and operating at higher voltages, as these advancements can directly increase the energy density and performance in demanding applications. Cathode materials must also be stable at high voltages and withstand repeated lithium insertion and extraction without significant structural degradation. This is crucial for long-term cycling stability and battery longevity. Charge transfer kinetics, which is the rate that charged particles can intercalate, is important for high-power applications [41]. Cathode materials must also be stable when in contact with the electrolyte at high voltages.

2.3.4. Interfacial Integrity

Interface engineering remains crucial to SSB performance, as it must allow seamless lithium-ion transport while minimizing resistance, thus maintaining efficient charge cycles and enhancing long-term stability [42]. The interface between the solid electrolyte and the electrode materials must maintain mechanical integrity during cycling [9]. As the battery charges and discharges, volume changes in the electrode materials can create stress, cracking, and gaps at the interface [43]. Hence, achieving consistent and low resistance contact between the solid electrolyte and electrode materials is a significant challenge. Consequently, scientists and engineers are investigating techniques such as interface coating, thermal treatment, and mechanical compression to optimize the interfaces.

During battery operation, a solid-state interphase (SSI) can form at the interface, similar to the SEI in liquid electrolytes [44]. This layer must be stable, thin, and conductive to lithium ions but insulating to electrons to prevent further reactions. The formation of a stable interphase is crucial for long-term battery performance as it protects the electrolyte and electrode from further unwanted reactions.

SSBs often require very thin layers of solid electrolyte to reduce internal resistance and ensure efficient ion transport. Creating these thin layers, especially in large-scale production, demands advanced techniques such as vapor deposition or sputtering, which are more complex and expensive

than the processes used for traditional batteries [23]. The manufacturing process must precisely stack multiple thin layers of anode, electrolyte, and cathode material with high alignment accuracy. Any misalignment can lead to poor performance or short circuits. Uniform pressure and precise alignment of SSB layers are essential for optimal performance, as even minor assembly defects can increase resistance, reduce ionic conductivity, and compromise cycle stability. The assembly equipment must carefully control the layering and compression to avoid damaging the materials or introducing defects. Improving yield while reducing defects is a critical issue in making solid-state batteries commercially viable. For solid-state batteries to become competitive, manufacturers must also reduce their costs significantly, which requires innovations in both materials and processes.

2.3.5. Battery Pack Development

The assembly of commercial lithium-ion batteries involves multiple stages, each contributing to the overall energy density and performance of the final battery. The assembly consists of three main levels: cell, module, and pack [16]. Cells can come in various formats, such as cylindrical, prismatic, and pouch cells. Prismatic and pouch cells can achieve higher energy densities due to better space utilization, as cylindrical cells often leave small gaps between them when arranged in a module [45].

Connecting multiple individual cells in series (to increase voltage) or parallel (to increase capacity) forms a module [46]. The arrangement depends on the application and the desired power and energy requirements. Modules often include cooling systems, protective casings, and safety features like thermal management and battery management systems. These additions help to prevent overheating, optimize performance, and ensure battery longevity. While cooling systems and safety features are essential for performance and safety, they can reduce the energy density at the module level by taking up space and adding weight. Efficient thermal management systems are crucial for minimizing this impact.

Multiple connected modules form a battery pack. The number of modules and their configuration (series or parallel) depend on the desired output voltage, capacity, and power of the battery. A sophisticated system monitors the health, temperature, and state of charge of each cell or module in the pack. The system ensures the safe operation of the battery, manages charging and discharging, and prevents overcharging, over-discharging, and overheating [47]. The arrangement of the pack casing and modules also affect the final energy density. In practice, the energy density at the pack level can be 10% to 25% lower than at the cell level due to the added weight and volume of these systems. Efforts to minimize the weight and size of the pack structure while ensuring safety and stability can help maximize the usable energy density of the pack.

Structural batteries are emerging as a manufacturing strategy that combines the functions of a battery and a structural component to significantly increase energy density [48]. The key is to make the battery itself a part of the structure of a device or vehicle, rather than a separate component that adds extra weight. Engineers can achieve this by using materials that can both store energy and bear mechanical loads. This approach will enable longer-range ground vehicles and new modes of transportation such as electric vertical takeoff and landing (eVTOL) aircraft [49].

3. Methodology

Figure 2 presents a detailed workflow illustrating the methodological approach used in the scientometric analysis. The selection of IEEE Xplore and Web-of-Science (WOS) as the primary databases for this analysis was based on their comprehensive coverage of high-impact, peer-reviewed research in the fields of science, technology, and engineering. The research community widely recognizes WOS for its multidisciplinary reach and robust citation tracking, while IEEE Xplore specializes in cutting-edge innovations in electrical engineering, computer science, and electronics. Scopus is another popular database used in literature reviews. However, the author could not utilize it due to institutional policy, given its considerable overlap with WOS and the need to manage research costs.

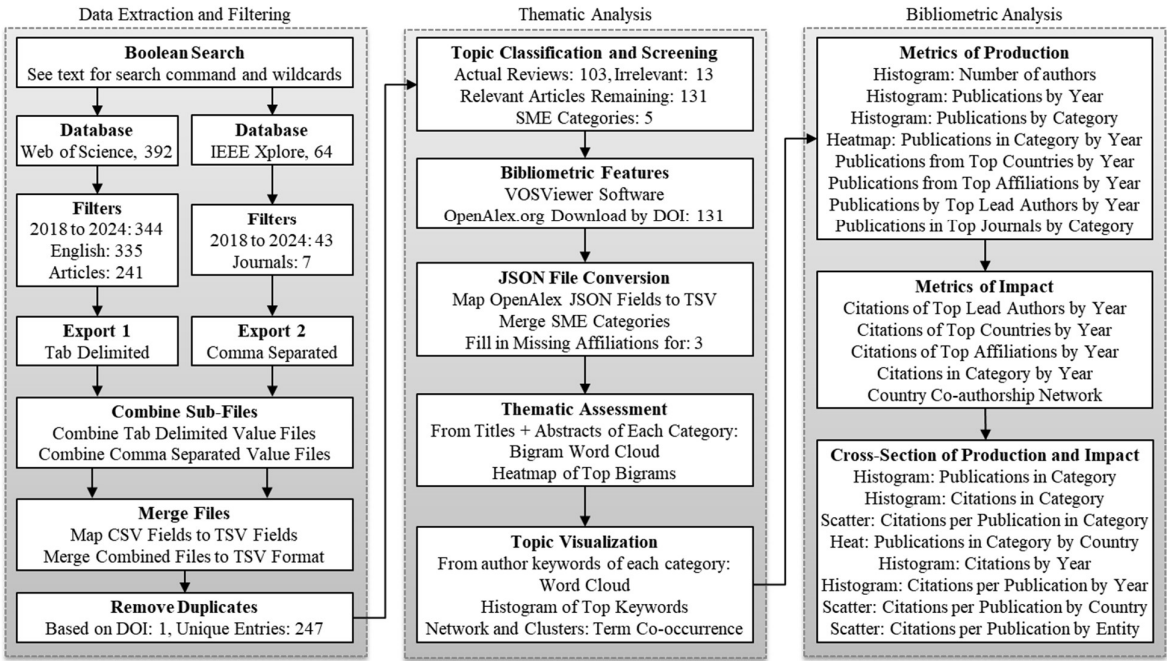


Figure 2. The workflow developed for the thematic and bibliometric analysis.

This study’s methodology used structured Boolean search commands, as shown in Table 1, across the databases to ensure comprehensive coverage of high-quality SSB publications, while excluding unrelated fields to maintain focus on high-power energy storage applications. The wildcard character “*” ensured that article titles contained variations of the term “solid-state,” such as “solid state,” “all-solid-state,” and “solidstate” plus variations of “battery” such as “batteries.” The search excluded articles with variations of the word “transformer” in the title because those discussed solid-state transformers rather than solid-state batteries. The WOS search provided flexibility to additionally search abstracts for the word “vehicle” or “vehicles,” ensuring a focus on high-power applications like electric vehicles. The author obtained the initial search results shown in Table 1 on October 13, 2024—these results were prior to filtering for publication years and article type.

Table 1. Data source, search commands, and initial results.

Source	Search Command	Results
IEEE	(“Document Title”:“solid-state” OR “Document Title”:“solid state” OR “Document Title”:“solidstate”) AND “Document Title”:batter* AND NOT “Document Title”:transformer*	64
WOS	(TI=((“solid-state” OR “solid state” OR “solidstate”) AND batter* NOT transform*)) AND AB=(vehicle*)	392
Google Scholar	allintitle: (battery OR batteries) AND (“solid-state” OR “solid state” OR “solidstate”) AND -transformer	3,270

The author also utilized the Google Scholar search engine to assess the overall landscape of research activity in SSB development. This wider view helped to assess the validity of the more focused results from the IEEE and WOS databases, while strengthening confidence that the selected articles have passed through more stringent quality filters. The author cautions that the wider cast of Google Scholar produced an order of magnitude more results due to automated crawling. Consequently, this search engine (not a database) captured multiple versions of the same article (including preprints and repository copies) and non-peer-reviewed content. Conversely, the WOS and IEEE databases utilize rigorous indexing criteria with manual verification, carefully removing

duplicates, and adhering to strict journal inclusion standards. The author verified that the superficially larger number of Google Scholar results included “gray” literature, conference proceedings, and articles from “predatory” journals, alongside entries of legitimate publications. Also, the Google Scholar search results included material covering developments outside high-power applications like electric vehicles. Cross-verification using Google Scholar validated the narrower, high-quality search results from IEEE and WOS, confirming that the sample focused specifically on rigorous, peer-reviewed SSB research relevant to high-performance applications.

The initial WOS search results showed that 2018 was the pivotal year when the number of publications rose sharply from 8 in 2017 to 10 in 2018. Therefore, the author filtered the search for English language articles from 2018 to 2024. This yielded 241 and 7 relevant articles from WOS and IEEE Xplore, respectively. The databases exported the results in different formats: tab-delimited for WOS and comma-separated for IEEE Xplore. The author wrote Python code to combine the sub-files, map fields from the different formats, and merge them into a unified tab-separated-value (TSV) format. The procedure searched for duplicate records based on their unique document identification (DOI) numbers and removed one, resulting in 247 unique entries.

Following the data collection, the author, a subject matter expert (SME), screened and categorized the filtered articles into distinct themes by reviewing the titles and abstracts. This step resulted in identifying and removing 103 review papers and 13 irrelevant articles, resulting in 131 final articles. Then using their DOI as a unique key, the VOSViewer software (version 1.6.20) downloaded their bibliometric features from the OpenAlex database into a JSON file [50]. After converting the JSON file to TSV format and merging back the SME defined categories, the author looked up and filled in 3 missing affiliations.

As shown in the workflow, the scientometric approach combined both thematic assessment and bibliometric analysis. The thematic assessment involved analyzing titles and abstracts using natural language processing (NLP) techniques to generate bigram word clouds and heatmaps. The author wrote Python code to clean, analyze, and visualize the downloaded bibliometric data by producing word clouds, histograms, heatmaps, scatter plots, and term co-occurrence networks of the most frequent keywords. The visualization procedures mapped the distribution of publications and citations across categories, authors, countries, and institutions. The author also carefully read the ten most recent publications within each category to offer some details and insights into their specific findings.

4. Results

The following subsections discuss the results of the SME categorization and the scientometric (thematic and bibliometric) analysis.

4.1. SME Categorization

In reviewing and screening the literature for relevance, the author categorized the various problems areas covered by the body of research and their interrelationships. Figure 3 highlights the problem categories in color. At the highest level of electrochemical and structural design, the critical research areas fall into four main areas: supply chain, capacity, charge kinetics, and cycling stability. The author further decomposed these into five technical metrics—supply chain efficiency in gigawatt-hours (GWh), energy capacity in milliampere-hours (mAh), ionic conductivity and interfacial resistance affecting charge kinetics in Siemens per centimeter (S/cm), and cycle stability measured by retention of a specified capacity at specific temperatures. These factors collectively impact performance, cost, safety, reliability, sustainability, and recyclability.

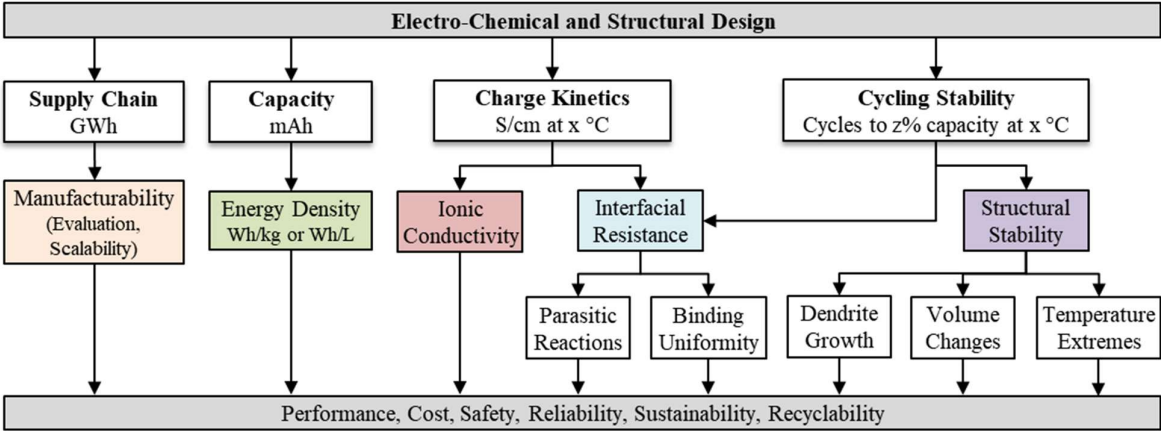


Figure 3. SME categorization of research thrusts.

The categorization framework shows how advances in materials and process design address interconnected challenges, such as low energy density, high interfacial resistance, and limited scalability, which collectively impact SSB performance, cost, and commercial viability. For instance, interfacial resistance stemming from parasitic reactions and non-uniform binding of electrode and electrolyte materials also affects cycling stability. Dendrite growth, volume changes, and temperature extremes affect structural stability, which also affects cycling stability.

4.2. Thematic Analysis

Figure 4 illustrates the thematic categorization of the SME defined research areas via bigram word clouds. The term font sizes are proportional to their relative frequency of occurrence in the corpus within each category, highlighting various research themes. The colors in the thematic word cloud visually distinguish research themes across categories like ionic conductivity, energy density, and interfacial resistance, helping to clarify distinct but overlapping areas within the broader SSB research landscape.

The bigrams “composite electrolyte” and “ionic conductivity” are key terms under cycling stability, emphasizing the importance of electrolyte materials in enhancing cycling performance. Under energy density, terms like “oxygen release” and “composite particle” reflect the focus on cathode and anode materials to improve discharge capacity. In the interfacial resistance category, “surface coating” and “interfacial impedance” are central, indicating ongoing efforts to mitigate resistance at the electrode-electrolyte interface. Meanwhile, manufacturability centers on techniques such as “x-ray imaging” and “machine learning” that aid in understanding underlying operating characteristics to inform production scalability. The “All Categories” section consolidates the most cross-cutting keywords, with “ionic conductivity” and “liquid electrolyte” emerging as dominant themes, highlighting their critical role across multiple areas of SSB research. Overall, this figure offers a visual overview of the interconnected focus areas within the field while validating the quality and accuracy of the filtering, screening, and categorization processes that isolated relevant articles in the SSB development domain.

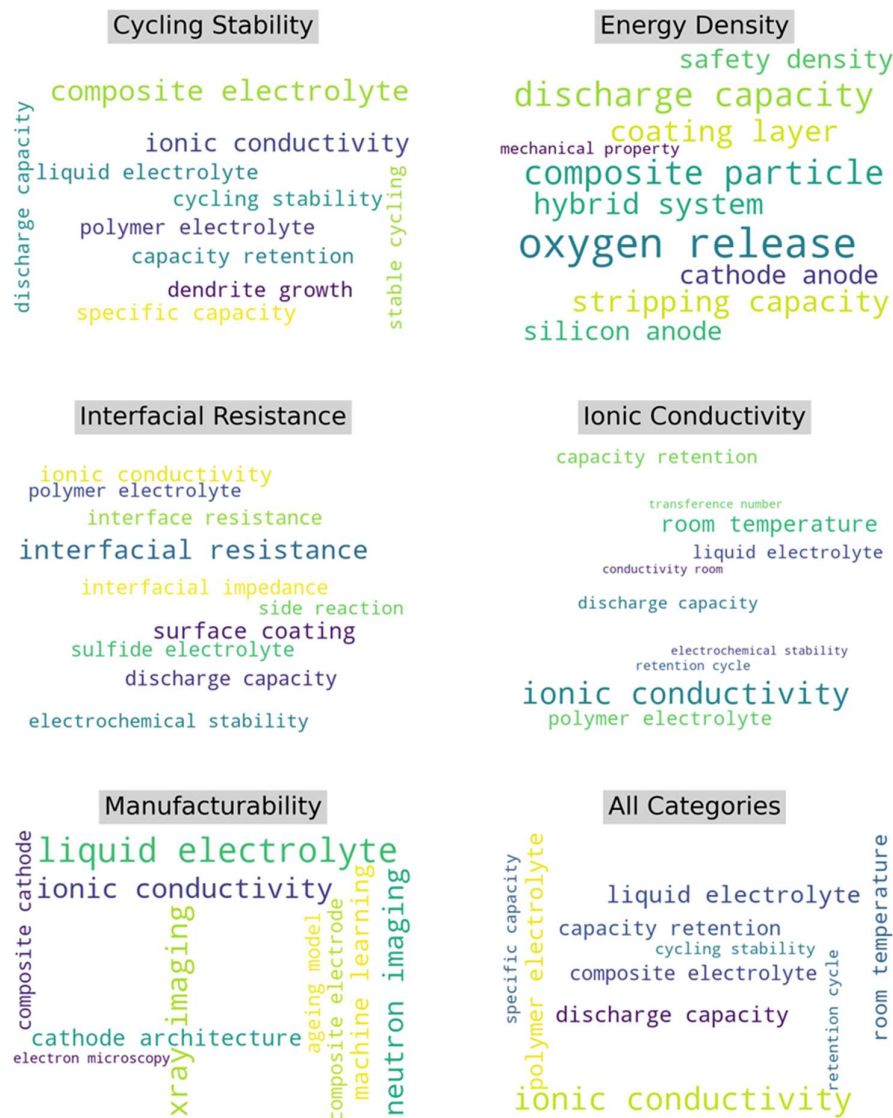


Figure 4. Bigram word cloud of titles and abstracts within each category.

Figure 5 are bar charts within each theme that complements the word cloud by showing how the 10 most frequent bigrams distribute. These frequency distributions provide a quantitative view of the research focus and the relative importance of the themes within each category. In the “Cycling Stability” category, “composite electrolyte” and “ionic conductivity” are the most frequent bigrams, followed by “specific capacity” and “liquid electrolyte,” indicating a research emphasis on the role of electrolyte materials in achieving stability during cycling. For the category of “Energy Density,” “oxygen release” dominates the distribution, reflecting the significance of material decomposition mechanisms, with other terms like “composite particle” and “discharge capacity” following closely.

In the “Interfacial Resistance” category, the term itself is the most discussed, with secondary focus on “surface coating” and “ionic conductivity,” highlighting the importance of interface engineering. The “Ionic Conductivity” category also shows a high frequency for the term itself and “room temperature,” highlighting the central focus on optimizing conductivity under practical conditions. Lastly, the “Manufacturability” category exhibits a more even distribution, with “x-ray imaging,” “neuron imaging,” and “machine learning” appearing frequently, reflecting the methods of evaluation applied towards understanding the underlying problems hindering production techniques. The distribution of bigrams across “All Categories” reveals that “ionic conductivity” is

the most widely studied research area, further emphasizing its critical role in advancing SSB technologies.

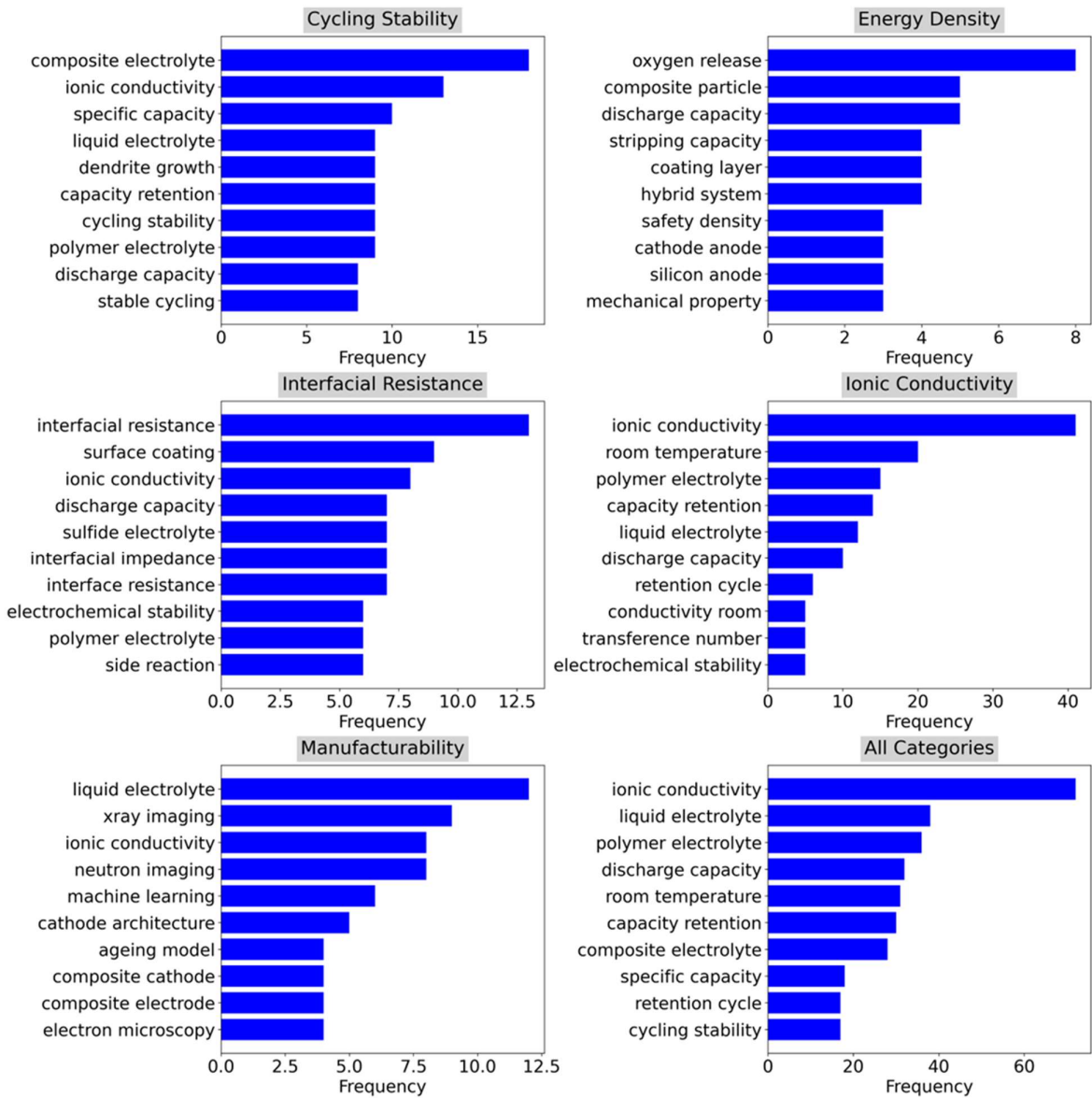


Figure 5. Bigram distribution of titles and abstracts within each category.

Figure 6 provides another view of the key themes from the perspective of the author-provided keywords across the five key research categories. In all categories, “electrolyte” emerges as the dominant keyword, highlighting its critical role in SSB research across various performance metrics. Terms like “fast conductor,” “sulfur,” “lithium,” and “nanostructured” appear prominently across multiple categories, reflecting a significant focus on improving electrolyte and electrode materials. In the “Cycling Stability” category, keywords such as “cathode,” “zinc ion,” and “nanostructure” indicate research aimed at improving the cycling performance of both electrolyte and electrode systems.

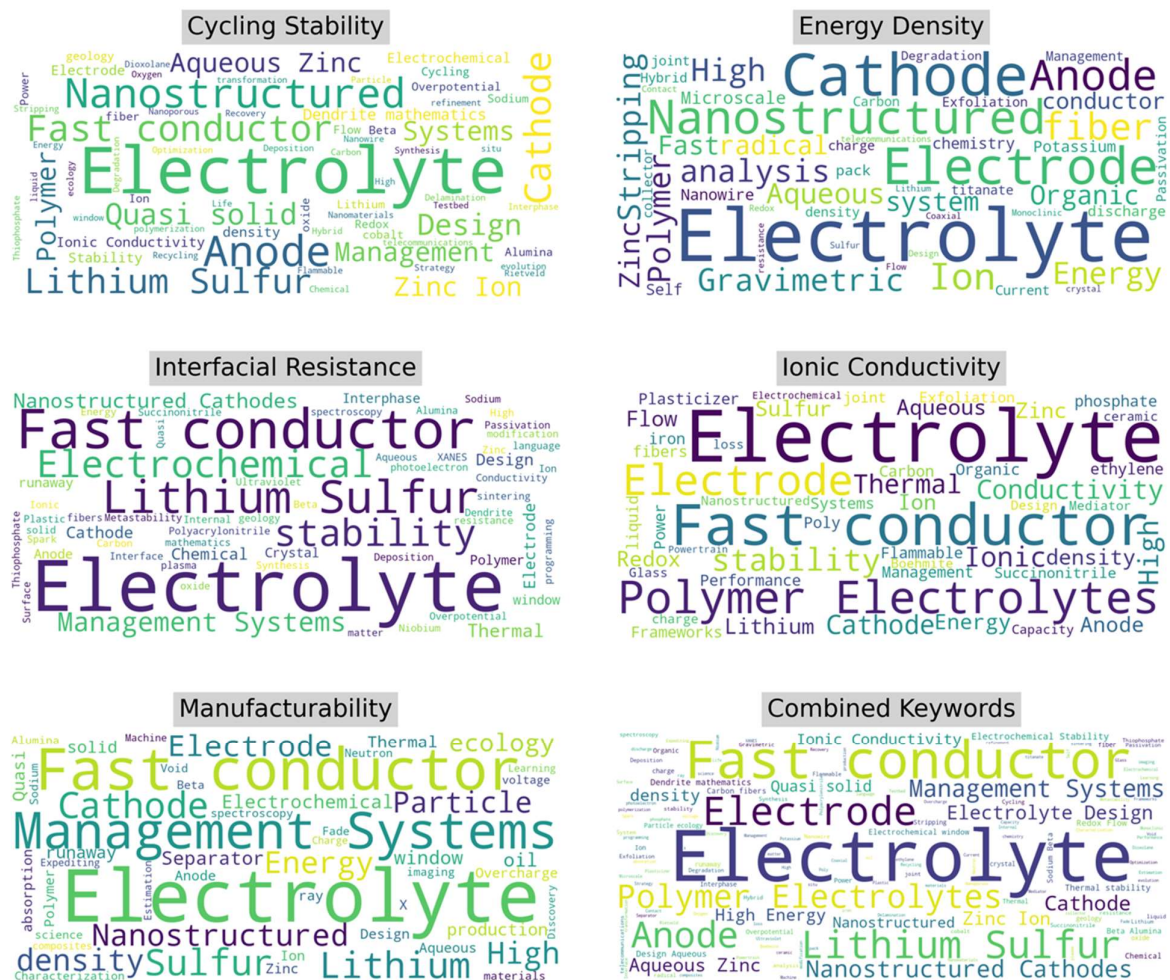


Figure 6. Categorical word clouds of author keywords.

For the “Energy Density” category, terms like “cathode,” “anode,” and “zinc stripping” highlight the focus on material optimization for enhancing energy storage capacity. The “Interfacial Resistance” and “Ionic Conductivity” categories share keywords such as “fast conductor” and “polymer electrolytes,” emphasizing the importance of mitigating resistance and enhancing ion transport at interfaces. Lastly, in the “Manufacturability” category, the recurrence of “management systems” and “lithium sulfur” reflects efforts to scale production while maintaining performance characteristics. The “Combined Keywords” cloud consolidates cross-cutting themes, where “electrolyte,” “fast conductor,” and “polymer electrolytes” dominate, indicating the foundational importance of these materials in advancing SSB technologies across all performance dimensions.

Figure 7 provides a cross-sectional visualization via a heatmap of the top five author keywords within each category. This resulted in 11 unique keywords represented in each row. Each column corresponds to one of the five SME defined research categories. The color intensity indicates the frequency of keyword occurrences, with darker blue shades representing fewer occurrences and darker red shades indicating higher frequencies. The keyword “electrolytes” is the most prominent, showing a high frequency across all categories, particularly in cycling stability (26 occurrences), interfacial resistance (21), and ionic conductivity (23). The keyword “fast conductor” also appears frequently in all categories except “energy density,” which is consistent with expectations. The keyword “anode” is primarily associated with cycling stability and energy density, reflecting the focus on anode material optimization.

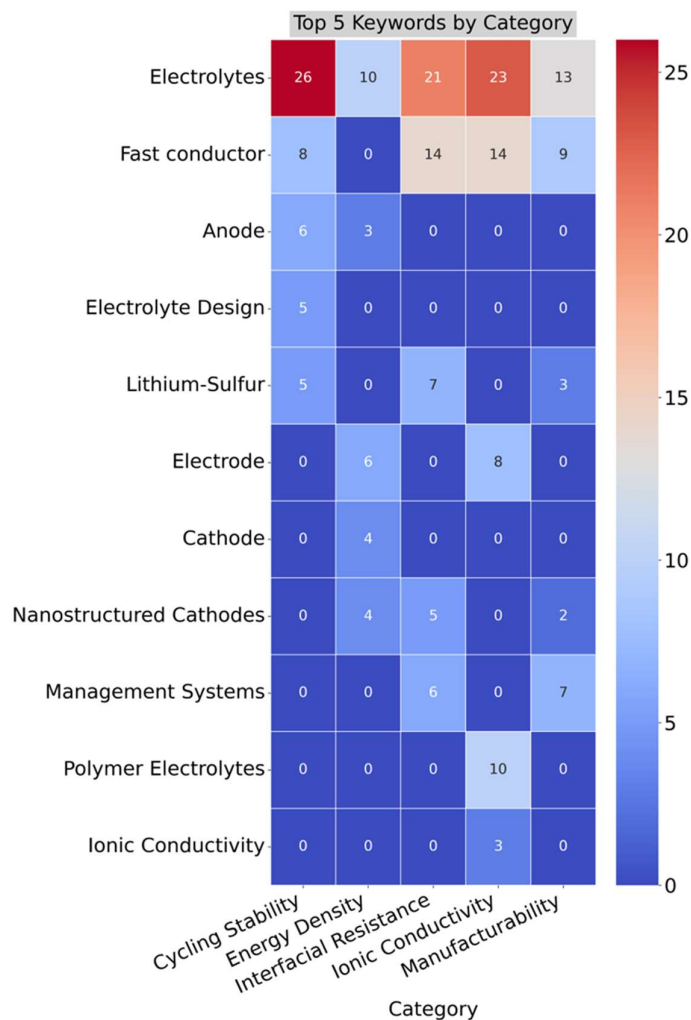


Figure 7. Cross sectional analysis of author keywords and research categories.

The keyword “electrolyte design” and “lithium-sulfur” have dominant co-presence in the cycling stability category, indicating ongoing research on advanced electrolyte formulations and sulfur-based systems to enhance stability. The high frequency of “polymer electrolytes” in the “Ionic Conductivity” category suggests emerging research to evaluate them as an intermediate solution to fully solid electrolytes. The category of manufacturability links strongly with “management systems” and “electrolytes,” highlighting their central role in developing scalable production techniques. Overall, this heatmap provides a clear cross-cutting overview of the distribution of specific research topics across the critical performance areas of SSBs.

Figure 8 presents a term co-occurrence network generated using VOSViewer, illustrating the relationships between key terms within SSB research. Each node represents a specific term, and the size of the node correlates with its frequency of occurrence in the corpus. The lines between nodes indicate co-occurrences, with the thickness of the lines representing the strength of the association between terms. The color coding reflects different clusters of closely related terms, indicating distinct thematic areas within the field.

The term “electrolyte” is central to the network, with strong connections to “ionic conductivity,” “stability,” “energy density,” and “anode,” illustrating its pivotal role across various research areas. Terms like “polymer,” “high ionic conductivity,” and “room temperature” linked to “ionic conductivity,” reflect the focus on improving conductive properties at practical operating conditions.

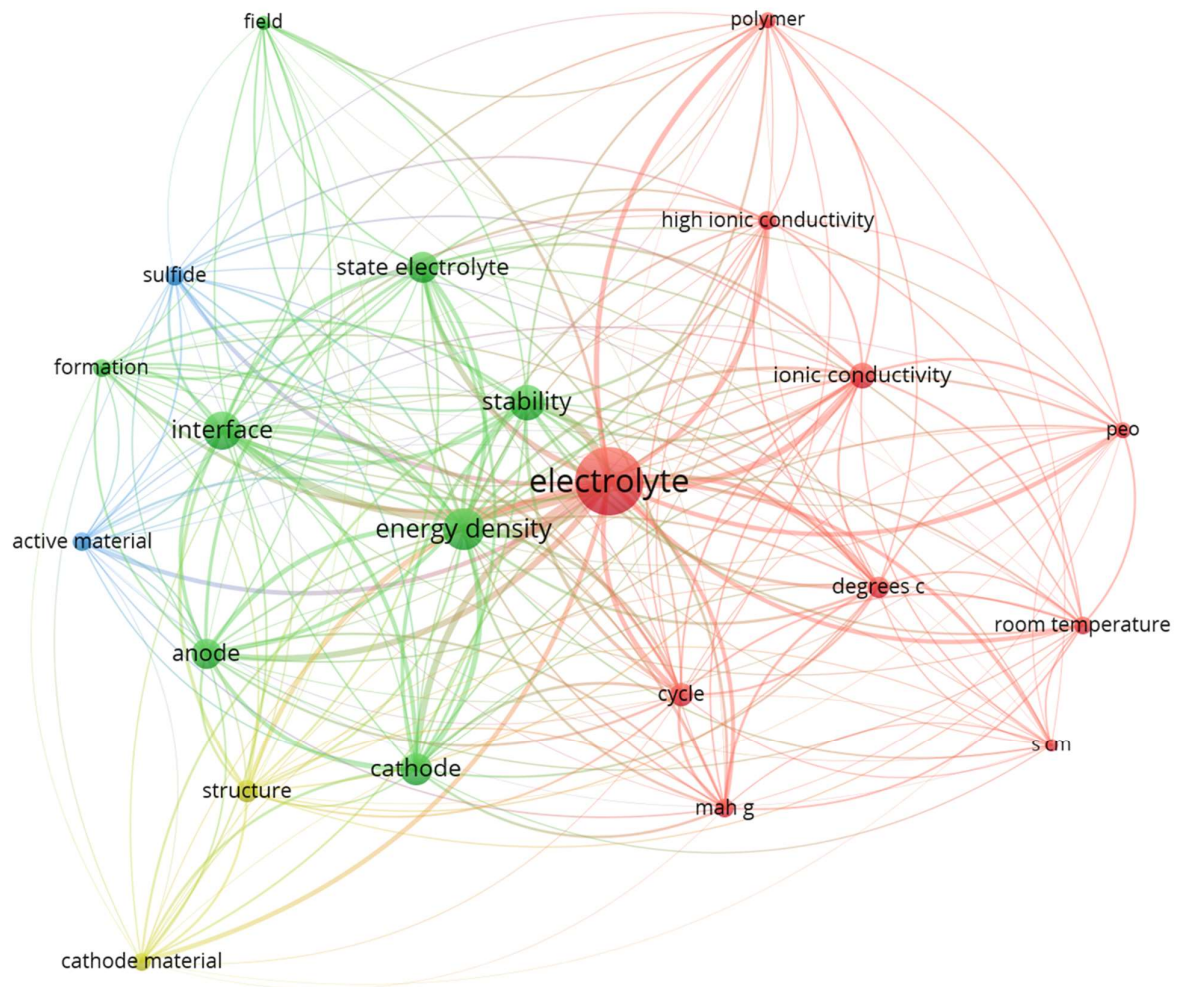


Figure 8. Keyword co-occurrence and cluster analysis.

On the energy side, the interconnection of terms like “cathode,” “energy density,” and “active material” indicate the importance of material selection in optimizing energy storage. The network also shows strong connections between “interface,” “stability,” and “[solid] state electrolyte,” suggesting that interfacial engineering and electrolyte design are critical for enhancing overall battery performance.

The term co-occurrence network also reveals distinct clusters that represent thematic groupings within SSB research. The color-code of each cluster signifies a concentrated area of focus. The red cluster, dominated by “electrolyte” and “ionic conductivity,” represents research centered around electrolyte materials and their conductivity properties, with significant attention on polymer-based electrolytes and room temperature performance. The green cluster, anchored by “energy density,” “cathode,” and “anode,” reflects the focus on optimizing electrode materials to enhance energy storage capacity, where cathode and anode designs play a critical role. The blue cluster, containing terms such as “active material” and “sulfide,” highlights studies on interfacial engineering, particularly the challenges of enhancing electrolyte/electrode interface stability and reducing interfacial resistance. Each cluster thus reflects a distinct yet interrelated avenue of research that collectively advances the development of SSB technology. Overall, this co-occurrence network visually maps the interconnected research themes, emphasizing the central role of electrolytes and the multidisciplinary efforts to improve both electrochemical performance and material stability.

4.3. Bibliometric Analysis

Figure 9 provides a quantitative analysis of publication trends in SSB research. Figure 9a shows a steady increase in the number of publications from 2018 to 2024, indicating growing research interest in the field. Figure 9b shows that most publications fall within the category on “Cycling Stability,” followed by “Interfacial Resistance” and “Ionic Conductivity,” while publications in “Manufacturability” and “Energy Density” are less prevalent. Figure 9c shows the distribution of authors per paper, with a mean of 7.28 authors, a standard deviation of 3.64, and a maximum of 24 authors, reflecting the collaborative nature of this research. Figure 9d is a heatmap that visualizes the distribution of publications by year and category, revealing a notable increase in publications related to “Cycling Stability” and “Ionic Conductivity” in recent years. Although having the second highest number of publications, research in the area of interfacial resistance has been steady over the years. Similarly, research in the areas of manufacturability and energy density has been steady over the years. Overall, this composite figure highlights the temporal and thematic evolution of research efforts, with a key finding that cycling stability and ionic conductivity have been key focal points in recent studies.

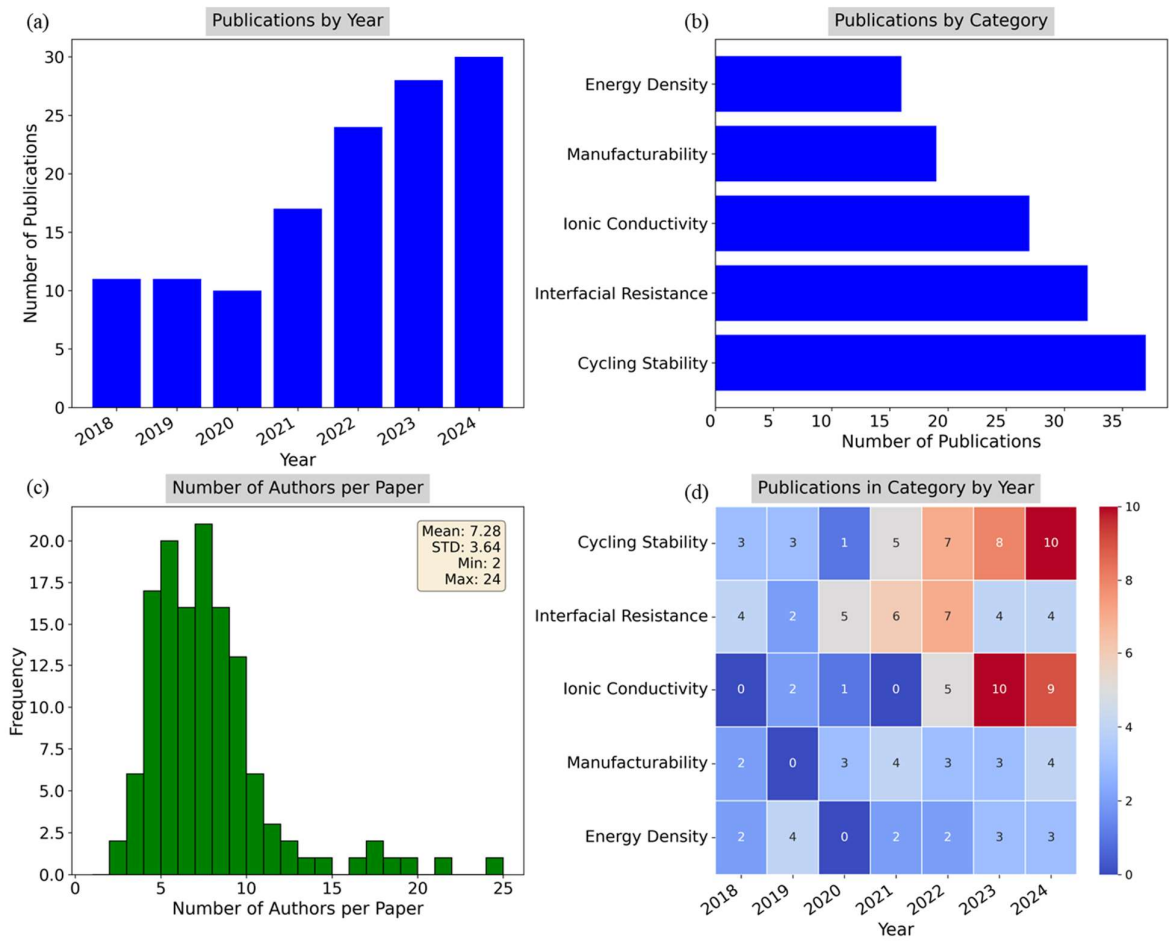


Figure 9. Publications by a) year, b) category, c) author distribution, d) category and year.

Figure 10 provides a detailed breakdown of publication patterns by top lead authors, countries, institutions, and journals in the field of solid-state battery research. Figure 10a highlights the top 10 lead authors, along with the number of unique co-authors (in parentheses). The figure shows that unique authors have contributed sporadically across the years with no author consistently dominating. Figure 10b reveals that China, Japan, and Korea dominate in publications over the years, with China leading the publications from 2021 onward. Figure 10c displays the top 10 affiliations of lead authors, showing that institutions such as the Korea Electrotechnology Research Institute and

Western University (Canada) have been most active, especially in recent years. Last, Figure 10d maps the publications by category and journal, showing that journals such as *Advanced Energy Materials* have published consistently across all categories. *ACS Applied Materials & Interfaces* showed a focus on cycling stability and interfacial resistance. Overall, this composite figure highlights the global and collaborative nature of SSB research, with a concentration of activity in East Asia and their prominent institutions driving advancements.

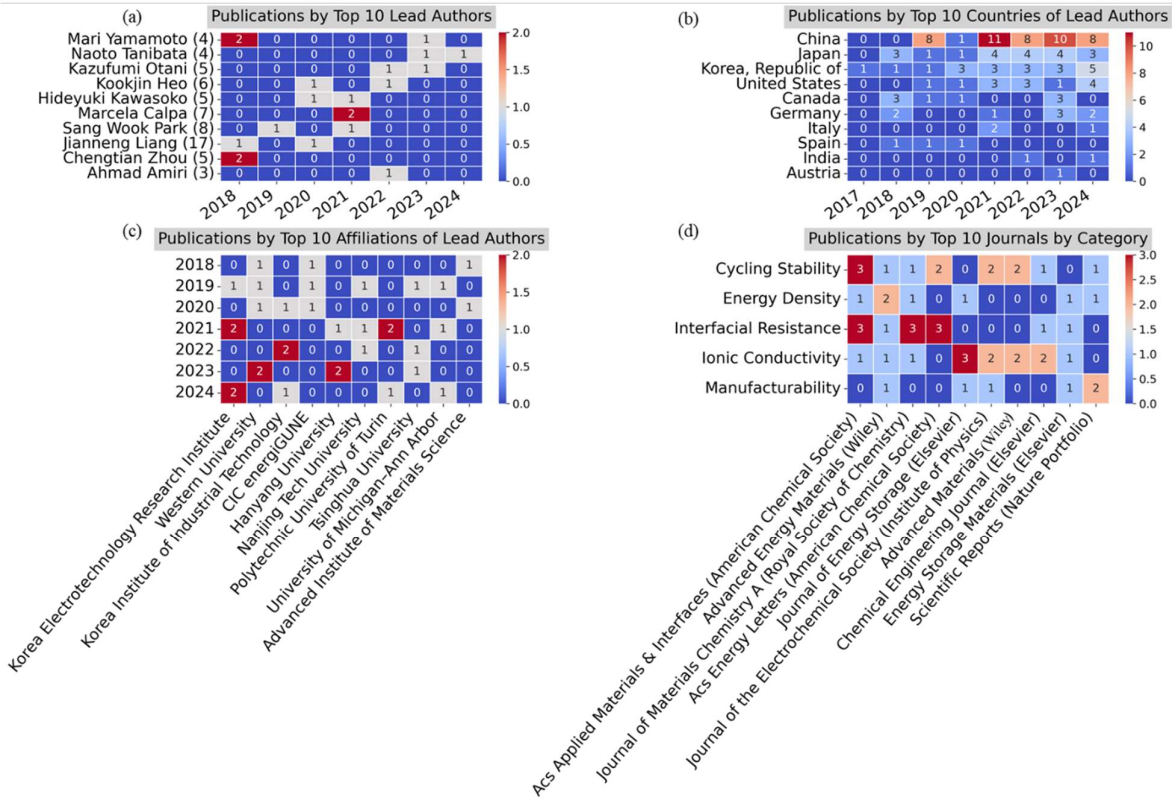


Figure 10. Publications by a) lead authors, b) countries, c) affiliations, and d) category and journal.

Figure 11 presents a comprehensive analysis of citation trends by lead authors, countries, institutions, and research categories in SSB research. Figure 11a shows the top 10 lead authors, with Young Jin Nam receiving the highest citation counts [51], particularly in 2023. Other authors, such as Mari Yamamoto [52] and Jianneng Liang [53], have seen substantial citation growth, reflecting their influential contributions in recent years. Figure 11b highlights the dominance of China and Korea in the citation landscape, with China seeing a sharp rise from 2021 onward, culminating in 347 citations before the end of 2024. Figure 11c shows citation counts by institution, where Western University and Ulsan National Institute of Science and Technology have garnered the most citations, especially since 2021, signaling their central role in advancing the field. Figure 11d categorizes citations by research categories, with “Interfacial Resistance” and “Cycling Stability” receiving the most attention, peaking in 2023 and 2024. Citations of papers focusing on manufacturability, ionic conductivity, and energy density showed steady increases over the years. Overall, the figure illustrates the growing academic impact of SSB research, with significant contributions from leading authors, institutions, and thematic areas.

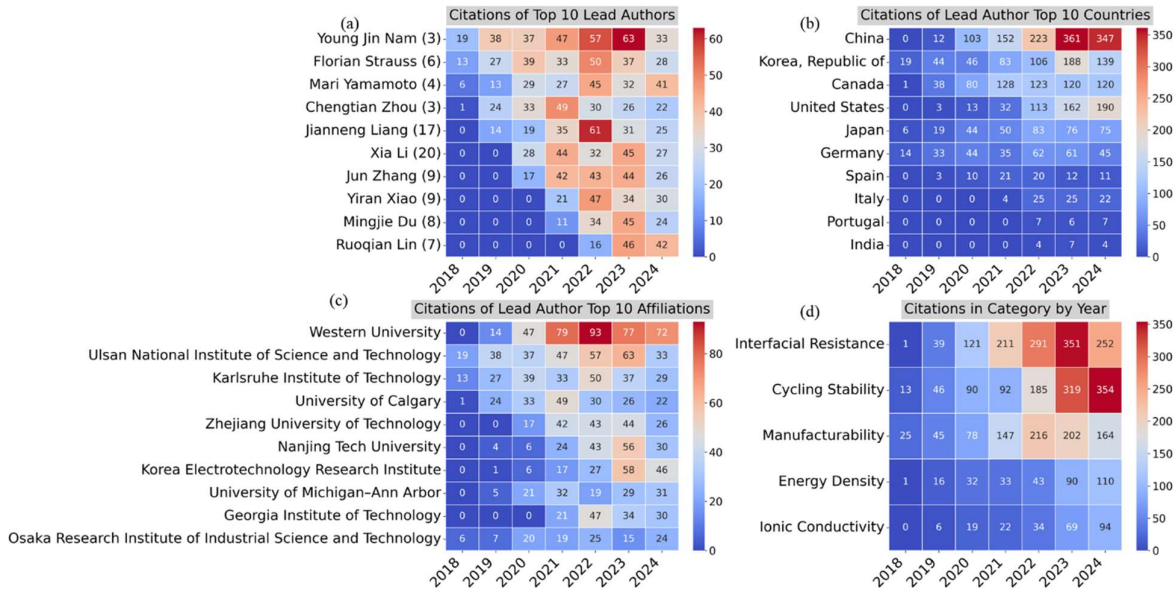


Figure 11. Citations by a) lead authors, b) countries, c) affiliations, and d) category and journal.

Figure 12 illustrates the country co-authorship network for SSB research, focusing on the six countries that have contributed to at least five publications. The node size reflects the number of documents, and the thickness of the connecting lines represents the strength of collaboration (link strength) between countries.

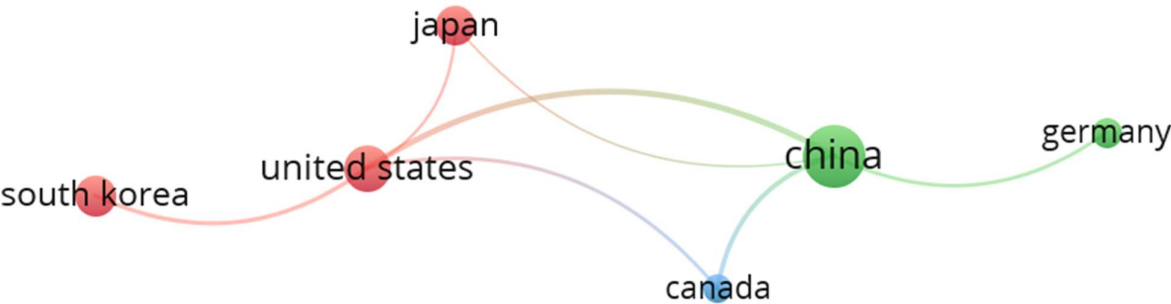


Figure 12. Country co-authorship network.

Table 2 further quantifies the number of documents, citations, and total link strength (TLS) for each country. China and the United States dominate the network, with the largest nodes and the strongest co-authorship links. They show significant collaboration with each other as well as with other countries like Canada, Japan, and the Germany. Interestingly, for this sampling of the literature, China had no co-authorship with South Korea, and the United States had no co-authorship with Germany. China led with 51 publications, 1,602 citations, and a TLS of 17 while the United States followed with 27 publications, 881 citations, and tied with a TLS of 17. South Korea ranked third in publications with 21 documents and 637 citations, but a much lower TLS of 4, indicating a lesser degree of international collaboration compared with China and the United States.

Table 2. Co-authored publications by countries.

Country	Documents	Citations	TLS
China	51	1602	17
United States	27	881	17

South Korea	21	637	4
Japan	20	378	3
Germany	12	408	3
Canada	11	632	8

Germany and Canada with 12 and 11 publications, respectively, exhibit moderate contributions to the field. Overall, the network highlights the global nature of SSB research, with the United States and China being central hubs for international collaboration and driving much of the citation impact in the field.

Figure 13 provides a detailed analysis of citation performance across different research categories in SSB studies.

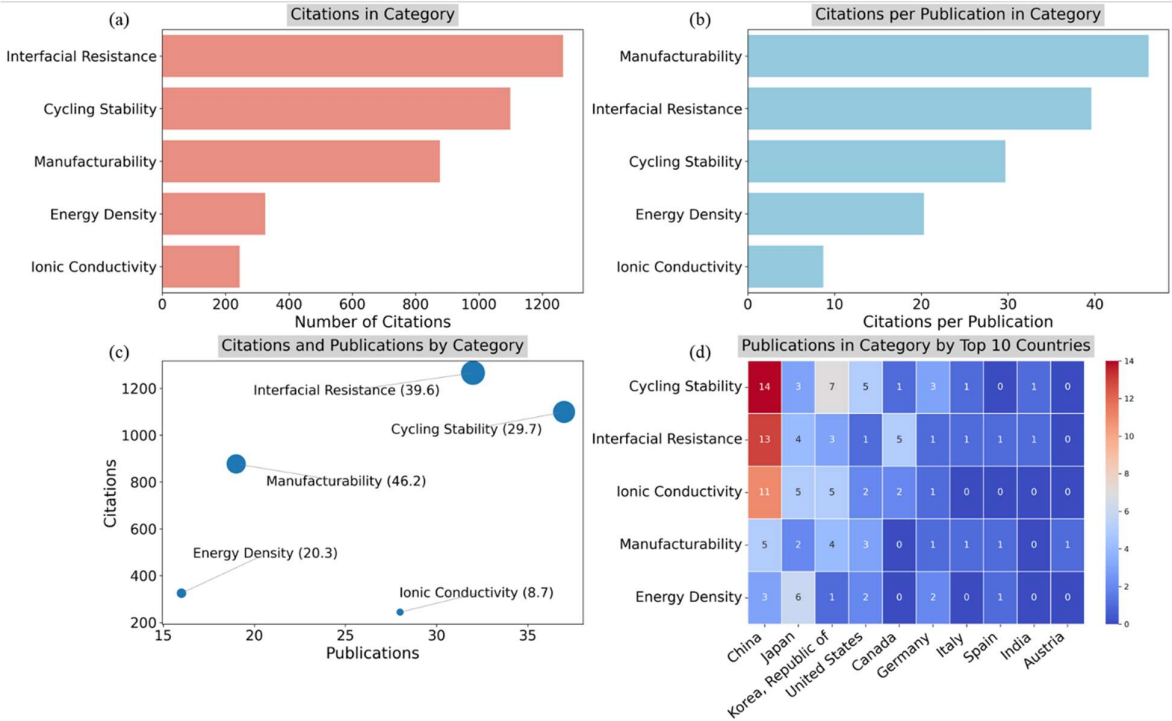


Figure 13. Citations a) across research categories, b) per publication within categories, c) rates in categories, and d) publications in category by top 10 countries.

Figure 13a shows that the categories of “Interfacial Resistance” and “Cycling Stability” received the highest number of citations, reflecting their centrality in SSB research. Figure 13b further breaks this down by citations per publication, where the category of “Manufacturability” leads with an average of more than 40 citations per paper, followed by the categories of “Interfacial Resistance” and “Cycling Stability,” indicating the high impact of research addressing scalability and interface challenges. Figure 13c provides a scatter plot of publications versus citations by category. Studies focused on cycling stability and interfacial resistance received both the highest publication and citation levels. The chart also shows that the category of “Manufacturability” has the highest citation-per-publication ratio (46.2), while “Ionic Conductivity” lags behind with a much lower ratio (8.7). This highlights a gap in that although fewer papers focused on manufacturability, they tend to have a significant impact. Figure 13d maps the distribution of publications by top 10 countries, showing that China leads in both the categories of “Cycling Stability” and “Interfacial Resistance,” while Japan and South Korea have balanced contributions across multiple categories. Overall, these visualizations illustrate the varying degrees of focus and academic influence across different areas of SSB research, with manufacturability and interfacial engineering emerging as high-impact topics.

Figure 14 provides a comprehensive overview of citation trends by year, country, and institutional affiliation in SSB research. Figure 14a shows a steady increase in total citations since 2018, reflecting the growing impact of research in this field. Figure 14b examines citations per publication by year, revealing a significant spike in 2020, followed by a decline in 2021, then a resurgence in subsequent years. Figure 14c highlights the distribution of citations and publications by country, where China leads in both. Canada, the United States, and South Korea also showed strong citation performance relative to their publication counts. Figure 14d shows the top affiliations by citations and publications, with Western University standing out in both dimensions. Overall, this composite figure illustrates the global and institutional dynamics of citation impact in SSB research, with leading countries and institutions showing strong research influence.

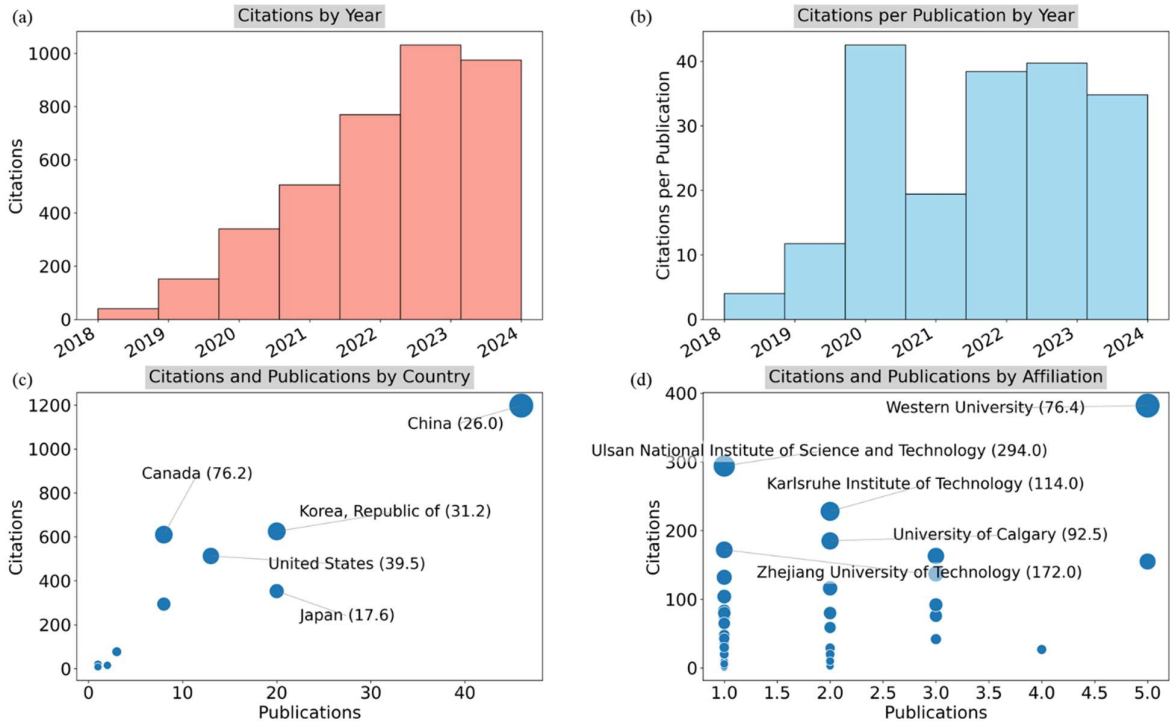


Figure 14. Citations a) by year, b) per publication by year, c) rates by country, and d) rates by affiliation.

5. Discussion of Key Findings

5.1. Ionic Conductivity

Table 3 summarizes findings from the ten most recent articles reviewed that focused on improving ionic conductivity. Low ionic conductivity remains a major barrier in SSBs, especially in lithium and lithium-sulfur compositions, where limitations restrict performance in high-power applications. Addressing this barrier requires breakthroughs in solid-state electrolyte designs to enhance ion transport while maintaining chemical stability. Solid polymer electrolytes, like polyethylene oxide (PEO)-based materials, have low ionic conductivity at room temperature, making them unsuitable for high-performance applications. This limitation highlights the need for materials that balance flexibility with high conductivity for better SSB performance.

Table 3. Ten most recent articles focusing on ionic conductivity.

Source	Key Findings
Choi et al. (2024)	Optimized wet process with sediment separation improves ionic conductivity and Li metal compatibility [54].

Song et al. (2024)	Solid halide electrolyte (Li ₃ VCi ₆) improves ionic conductivity and increases energy density by serving as both an active electrolyte and catholyte [5].
Xu et al. (2024)	Cellulose-based eutectogel electrolyte (CETG) with dual ion conduction mechanisms improves ionic conductivity, self-healing, and cycling stability in LiFePO ₄ cells [55].
Sung et al. (2024)	A novel, scalable wet synthesis method produces Li _{5.5} PS _{4.5} Cl _{1.5} with high ionic conductivity (4.98 mS/cm) and uniform particle size, optimizing interfacial contact and enhancing discharge capacity [8].
Zhao et al. (2024)	Adding larger-grain boehmite nanoparticles to PEO-based electrolytes improves Li ⁺ transference, ionic conductivity, and stability, enabling enhanced cycling performance in lithium metal batteries [56].
Nam et al. (2024)	LTPO (LiTa ₂ PO ₈) solid-electrolyte disks, synthesized via cold sintering, combined with lithium manganese iron phosphate (LMFP) electrodes improve ionic conductivity and stability, achieving 98% capacity retention after 100 cycles at room temperature [57].
Choi et al. (2024)	Separating the precipitate and removing the supernatant after high-energy ball milling increases the ionic conductivity and compatibility of solid electrolyte with lithium metal at room temperature [54].
Abe et al. (2024)	A flexible PEO-based composite electrolyte with Li _{6.4} La ₃ Zr _{1.4} Ta _{0.6} O ₁₂ and liquid plasticizers achieves high lithium-ion conductivity of 6.01×10 ⁻⁴ S/cm at 25 °C while preventing dendrite formation [3].
Thomas et al. (2024)	A scalable liquid-phase exfoliation process produces kaolinite nanoplatelets, enabling the creation of a nanocomposite gel electrolyte with high ionic conductivity and stability, suitable for high-rate rechargeable lithium metal batteries [1].
Kwok et al. (2023)	A Li ₂ S/LiVS ₂ core-shell cathode architecture improves ionic mobility, leading to good rate capability and stable capacity retention [58].

Solid-state electrolytes like Li₆PS₅Cl and LAGP (lithium-aluminum-germanium-phosphate) chemistries face synthesis-related challenges, where residual solvents and low-density microstructures reduce conductivity. Composite cathodes with solid-state electrolyte additives often compromise ionic transport and energy density, suggesting that optimized composite designs are essential for maximizing both conductivity and storage capacity without sacrificing efficiency. The ionic conductivity challenge deeply interlinks with interfacial resistance and cycling stability, indicating that future SSB research should adopt an integrated approach that addresses ion transport efficiency along with interface optimization and stable cycling performance. For instance, phase instability and slow ion transport in solid-state electrolytes elevate interfacial resistance and hinder ion dissociation. Developing solid-state electrolytes that balance high ionic conductivity, stability, and effective ion/electron pathways remains critical for achieving efficient, fast-charging SSBs for high-demand applications.

5.2. Interfacial Resistance

Table 4 summarizes findings from the ten most recent articles reviewed that focused on improving interfacial resistance. Poor compatibility between solid electrolytes and electrodes, such as low wettability and phase separation, impedes ion transport and charge transfer efficiency, highlighting the importance of developing interface materials and treatments that maintain stable, low-resistance connections under cycling conditions. Cathodes with high Ni oxide composition and sulfide-based solid electrolytes are prone to side reactions and chemical instability, which degrade interfacial integrity and also limit cycle stability. Similar to ionic conductivity, interfacial resistance challenges interconnect with overall cycling stability and energy density. Innovations here must, therefore, target interface coatings and structural modifications that enable seamless lithium-ion transfer and sustained cycle life. For instance, in Na and Li-ion batteries, grain boundary resistance, microcrack formation, and poor solid-solid contacts elevate internal resistance, which also lowers ionic conductivity and power delivery. Thermal and mechanical instability at interfaces, particularly in garnet type solid electrolytes, further compromises SSB performance. Resolving interfacial

resistance demands the development of stable, thin, and ion-conductive layers that prevent parasitic reactions and reduce insulating byproduct formation, thus improving both the safety and performance of SSBs for real-world applications.

Table 4. Ten most recent articles focusing on interfacial resistance.

Source	Key Findings
Shao et al. (2024)	TM-MES (C ₉ H ₂₂ O ₅ Si) improves phase compatibility, ionic conductivity, and cycling performance in Li-S SSBs, achieving high energy density [59].
Cha et al. (2024)	Halide-coated NCM (LiNi _x Co _y Mn _z O ₂) electrodes reduce interfacial resistance and improve rate capability and cycling stability, with performance dependent on halide composition [60].
Terashima et al. (2024)	Surface coatings, such as LiNbO ₃ , protect NCM cathodes by mitigating side reactions, improving interface stability and enhancing battery performance [61].
Liang et al. (2023)	LLZO (Li ₇ La ₃ Zr ₂ O ₁₂) coatings on LiCoO ₂ cathode improve cycling performance and discharge capacity in thiophosphate-based SSBs [62].
Liu et al. (2023)	A LiNbO ₃ coating creates a passivation layer at the cathode-electrolyte interface, reducing interfacial degradation and achieving 82% capacity retention after 2000 cycles at 1 °C [63].
Guan et al. (2022)	Bending effects alleviate interfacial stress, and improving contact area and curvature enhances cell capacity and stability in flexible SSBs [64].
Tanibata et al. (2023)	The Na ₁₀ Sn ₄ metastable phase exhibits fast Na diffusivity and low interfacial resistance, enhancing battery performance [65].
Heo et al. (2022)	Compositing LLZAO (Li _{6(,75)} La ₃ Zr ₂ Al _{0.25} O ₁₂) with NCM811 (LiNi _{0.8} Co _{0.1} Mn _{0.1} O ₂) cathode reduces interfacial resistance and improves cycling stability and rate performance [66].
Saffirio et al. (2022)	The addition of diboron trioxide (B ₂ O ₃) improves grain cohesion, reduces grain boundary resistance, and enhances ion mobility, making the glass-ceramic based on Li _{1.4} Al _{10.4} Ge _{0.4} Ti _{1.4} (PO ₄) ₃ solid state electrolyte promising for high-energy density, safe lithium-based batteries [67].
Zhao et al. (2022)	A SnS ₂ ultra-thin film on LLZTO (Li _{6.75} La ₃ Zr _{1.75} Ta _{0.25} O ₁₂) forms a Li ₂ S/Li _x Sn conductive layer through a conversion reaction with molten Li, reducing interfacial impedance and inhibiting dendrite growth [68].

5.3. Cycling Stability

Table 5 summarizes findings from the ten most recent articles reviewed that focused on improving cycling stability.

Table 5. Ten most recent articles focusing on cycling stability.

Source	Key Findings
Zhu et al. (2024)	Doping a lithium-aluminum-titanium-phosphate (LATP) solid-state ceramic electrolyte with zinc strengthened its mechanical properties while providing an optimized network channel for lithium-ion transport at room temperature [69].
Kreissl et al. (2024)	Fe-substitution in SnO ₂ and ZnO anodes enhances cycling performance by mitigating degradation in Li ₆ PS ₅ Cl-based SSBs [70].
Ma et al. (2024)	Oxyhalide-nitride solid electrolytes (ONSEs) exhibit high dendrite-suppression capabilities, improved thermodynamic stability, and enable long-term cycling, achieving 90% capacity retention over 500 cycles [71].
Jiang et al. (2024)	Bi-O dual-doping in Li _{5.5} PS _{4.5} Cl _{1.5} electrolyte improves air/moisture stability, enhances Li dendrite suppression, and accelerates Li-ion transport. The resulting electrolyte, Li _{5.54} P _{0.98} Bi _{0.02} S _{4.47} O _{0.03} Cl _{1.5} , achieves superior cycling performance with a Li metal anode, retaining 79.7% capacity after 150 cycles at 25°C using LiCoO ₂ and high-nickel cathodes [72].
Zhou et al. (2024)	A conductive S _{9.3} I molecular crystal with iodine insertion enhances electrical conductivity and enables interface repair through remelting, improving cycling stability and capacity retention [73].

Kim et al. (2024)	Substituting lithium with cadmium in the solid electrolyte induces structural distortion and enhances stability, significantly improving critical current density and cycling performance [7].
Lu and Birke (2024)	A dual-layered anode with a thin zinc layer (286 nm) and carbon black improves cycling stability and discharge capacity retention by optimizing lithium-zinc alloying behavior [74].
Kim et al. (2023)	B doping and coating of a Ni-rich cathode improves microstructure and interface stability [75].
Li et al. (2023)	Precise tailoring of Li-ion transport in Li_3InCl_6 halide solid electrolytes boosts lithium-ion conduction and dendrite suppression, significantly improving cycling life and capacity retention [31].
Du et al. (2022)	A flexible SSB with a V_2O_5 nanowire-carbon-nanotube composite cathode and silver nanowire/lithium composite anode enhances cycle stability and inhibits Li dendrite growth, achieving stable performance over 500 cycles [76].

As with the previous categories, the issues in this category are also interdependent. For instance, high interfacial resistance, ion transport limitations, and Li dendrite growth with lithium metal anodes complicate energy density optimization across different chemistries. Studies in this area focus on mitigating lithium dendrite growth and enhancing interfacial stability, emphasizing the need for dendrite-suppressing materials and coatings that protect electrode integrity while maintaining high energy density over extended cycling periods. Sulfide and polymer electrolytes suffer from poor air/moisture stability and limited lithium-ion conductivity, affecting cycle life and stability, especially in high-energy configurations. Silicon and sulfur anodes exhibit significant volume expansion, challenging the structural integrity of SSBs. Developing flexible or adaptive electrolyte materials and engineered anode architectures are crucial for maintaining stability and capacity retention over repeated cycles. Additionally, the insulating nature of some active materials and poor interfacial contact increase resistance, highlighting the need for materials that ensure continuous, low-resistance pathways to sustain high cycling efficiency and minimize energy losses. These issues, coupled with side reactions and structural instability, highlight the need for advancements in materials that balance ionic/electronic conductivity, mechanical durability, and compatibility across wide temperature ranges for effective performance.

5.4. Energy Density

Table 6 summarizes findings from the ten most recent articles reviewed that focused on improving energy density.

Table 6. Ten most recent articles focusing on energy density.

Source	Key Findings
Han et al. (2024)	A core-shell approach using $\text{Li}_6\text{PS}_5\text{Cl}$ and LiNbO_3 coatings on $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$ particles enhances cathode active material utilization, resulting in improved ionic conductivity and a dense microstructure. This design achieves a reversible capacity of 197 mAh/g and excellent cycling performance with 86.3% retention after 1000 cycles at 2 °C [77].
Lee and Sakamoto (2024.	Surface modification of garnet electrolytes and intermittent-current stripping improve stripping capacity and suppress void formation in Li by 40% [78].
Tanibata et al. (2024)	NaFeCl_4 , with a high redox potential and deformability, offers improved energy density and safety [79].
Xiong et al. (2023)	High-concentration PEO electrolytes resist oxidation and improve cycling stability with high-voltage cathodes and enhances energy density [80].
Poetke et al. (2023)	Partial lithiation of silicon microparticles with reduced charge cut-off potential improves capacity retention and energy density in NCM cells [81].
Hayakawa et al. (2022)	Incorporating acetylene black into the SE coating layer improves cell capacity and rate performance [82].
Xu et al. (2019)	SSBs with $\text{Li}_7\text{P}_3\text{S}_{11}$ electrolyte, silicon anode, and Li_2S /graphene cathode achieves high energy density and improved safety without using metallic lithium [83].

Martinez et al. (2019)	A catholyte fraction of 30-40% ensures good interfacial contact and ionic transport, enabling theoretical energy densities up to 185 Wh/kg and 345 Wh/L [84].
Wang et al. (2019)	Lithium-depleted $\text{Li}_{0.33}\text{MnO}_2$ is a cost-effective, cobalt-free cathode material, offering improved cycling stability by reducing manganese dissolution and enhancing gravimetric energy density [85].
Huang et al. (2018)	A graphene-based quasi-solid-state lithium-oxygen battery with a 3D porous graphene cathode, redox mediator-modified gel polymer electrolyte, and porous graphene/Li anode overcomes key challenges, achieving higher gravimetric and volumetric energy densities than commercial Li-ion polymer batteries [86].

Research highlights that poor cathode utilization and low percolation rates reduce accessible capacity in SSBs. Optimizing cathode architectures and ensuring uniform ion pathways are essential to achieving the high energy density needed for electric vehicles and grid storage. In anode-free designs, limited stripping capacity of lithium restricts potential energy. Structural degradation from oxygen release in layered cathodes and the oxidative instability of PEO electrolytes with high-voltage cathodes further lower energy density. Alternative chemistries, such as sodium-ion and metal-air batteries, also face performance limitations, with sodium-ion lacking both energy efficiency and cost viability for large-scale use. Volume changes in silicon anodes and insufficient conductive contact in solid-electrolyte-coated materials hinder capacity retention. Achieving the right balance of energy density, safety, and stability is essential for SSBs, particularly for high-power applications. Efforts in cathode and electrolyte design should therefore focus on maintaining structural integrity and conductive pathways while avoiding degradation over extended use.

5.5. Manufacturability

Table 7 summarizes findings from the ten most recent articles reviewed that focused on manufacturability challenges.

Table 7. Ten most recent articles that focused on manufacturability.

Source	Key Findings.
Choi et al. (2024)	Dual-doped sulfide electrolyte improves air stability, ionic conductivity, and Li metal compatibility towards scalable manufacturing [4].
Wach et al. (2024)	Laser cutting technology improves edge quality of sulfide-based components, advancing the production process for SSBs [87].
Basak et al. (2023)	Using in-situ transmission electron microscopy on Si nanoparticles enables efficient screening of potential coatings to improve interface stability in SSBs [88].
Cao et al. (2023)	Neutron imaging provides nondestructive operando visualization of Li dynamics and reaction mechanisms, offering insights towards SSB manufacturing [89].
Yoon et al. (2022)	Storage at 70 °C causes significant degradation of $\text{Li}_6\text{PS}_5\text{Cl}$, leading to SO_x gas evolution, porous cathode/electrolyte interfaces, and increased interfacial resistance, highlighting the need to reassess solid electrolyte stability [90].
Song et al. (2022)	Controlling particle size of Ni-rich NCM811 cathode improves electrochemical performance in SSBs with composite solid electrolytes [91].
Lou et al. (2021)	Synchrotron X-ray imaging provides real-time insights towards manufacturing SSBs [92].
Ge et al. (2021)	A novel green solid polymer electrolyte made from ionic liquid-based waterborne polyurethane and LiClO_4 achieves high conductivity without the use of organic solvents, offering a safe and eco-friendly alternative for SSBs [93].
López-Aranguren et al. (2020)	NMC622 cathode with PEO-based electrolyte and Li metal anode delivers 91% of theoretical capacity, demonstrating feasibility for industrial-scale SSB development [94].
Zhang et al. (2019)	In situ electrochemical impedance and Raman spectroscopy show that Li^+ ion migration, varying with potential change, significantly impacts the interface, contributing to SCL, interfacial reactions, and long-term deterioration of electrochemical performance [95].

Scalable manufacturing remains a critical barrier to SSB commercialization, with issues such as moisture sensitivity, material compatibility, and environmental impact of production methods highlighting the need for greener, cost-effective approaches in SSB fabrication. Sulfide solid electrolytes like $\text{Li}_6\text{PS}_5\text{Cl}$ are highly moisture-sensitive and incompatible with lithium metal, presenting challenges for both long-term stability and safety. Manufacturers can resolve these issues through protective coatings or alternative stable electrolyte materials. Limitations in scalable fabrication methods for high-capacity SSBs restrict production viability. The use of harmful solvents in slurry-based processes and reliance on binders for electrode stability introduce environmental and health concerns. Additionally, the lack of understanding interparticle stress hinders the development of processes to ensure long-term reliability. Furthermore, the high cost of inorganic electrolyte manufacturing poses economic barriers. Consequently, scaling SSB production to competitive levels requires advancements in materials that ensure high energy density, structural integrity, and safety, along with manufacturing methods that minimize defects and environmental impact, paving the way for sustainable commercial applications.

5.6. Limitations and Future Works

Despite the comprehensive insights gained from this scientometric analysis, several limitations highlight areas for future exploration. This study primarily focused on high-impact research categories within the fields of ionic conductivity, interfacial resistance, cycling stability, energy density, and manufacturability. However, other critical areas such as environmental impact assessment and recycling methods were beyond its scope. Additionally, while the analysis utilized data from IEEE Xplore and Web of Science databases, future studies could benefit from integrating more databases like Scopus to identify and assess any gaps. Moreover, this study's focus on bibliometric patterns and keyword frequency trends provided valuable high-level insights but did not allow for in-depth experimental comparisons or evaluations of specific SSB chemistries.

Future work could apply advanced machine learning techniques to bibliometric datasets to predict emerging trends or synthesize experimental findings across subfields, offering an extended perspective on SSB advancements. Expanding the analysis to include life-cycle assessments, cost-benefit evaluations, and the environmental implications of scaling SSB production would also provide essential context for stakeholders aiming to transition from research to commercial deployment. These additional areas, while valuable, would diverge from the core thematic and bibliometric focus of the current work, offering a rich direction for future studies.

6. Conclusions

Solid-state batteries (SSBs), particularly lithium-based systems, represent a transformative advancement in energy storage, promising to address key challenges in safety, energy density, and longevity faced by conventional lithium-ion batteries. They offer potential solutions to the safety, energy density, and longevity challenges faced by conventional lithium-ion batteries. This research conducted a detailed scientometric analysis, revealing critical areas like ionic conductivity, interfacial resistance, and manufacturability as bottlenecks in achieving high-performance SSBs, particularly for applications in electric vehicles. The findings highlight substantial progress in areas such as electrolyte optimization and interfacial engineering but underscore remaining challenges, notably in developing scalable manufacturing methods and enhancing ionic conductivity at room temperature. Collaborative research increasingly emphasizes high-ion-conductivity electrolytes, interfacial stability, and scalable designs, showing strong advancements in SSB reliability but with notable gaps in achieving industry-wide manufacturing feasibility. Sustained efforts in materials optimization, particularly in polymer and sulfide-based electrolytes, as well as robust interface design, will be essential to enhance SSB cycle stability and manufacturability, driving them closer to commercial application. These advances have the potential to pave the way toward safer, higher-density energy storage solutions, essential for achieving long-range electric mobility and efficient grid storage systems, contributing to a sustainable energy future.

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References

- [1] C. M. Thomas, D. Zeng, H. C. Huang, T. Pham, C. G. Torres-Castanedo, M. J. Bedzyk, V. P. Dravid and M. C. Hersam, "Earth-Abundant Kaolinite Nanoplatelet Gel Electrolytes for Solid-State Lithium Metal Batteries," *ACS Applied Materials & Interfaces*, vol. 16, no. 27, p. 34913, 2024.
- [2] S. Kumar, K. Chakravarty, K. Kumar, A. Sen, C. Ghanty, S. Chakravarty and R. Kundu, "Solid-State Direct Regeneration of Spent Lithium Cobalt Oxide Cathodes for Li-Ion Batteries," *Energy & Fuels*, vol. 38, no. 7, p. 6499, 2024.
- [3] A. Abe, D. Mori, Z. Wang, S. Taminato, Y. Takeda, O. Yamamoto and N. Imanishi, "Flexible High Lithium-Ion Conducting PEO-Based Solid Polymer Electrolyte with Liquid Plasticizers for High Performance Solid-State Lithium Batteries," *ChemistryOpen*, vol. , p. , 2024.
- [4] Y. J. Choi, Y. J. Hwang, S.-I. Kim, M.-J. Kwak and T. Kim, "Triple-Doped Argyrodite Sulfide Electrolyte with Improved Air Stability and Lithium Compatibility for All-Solid-State Li Metal Batteries," *Chemical Engineering Journal*, vol. 497, p. 154426, 2024.
- [5] Z. Song, Y. Dai, T. Wang, Q. Yu, X. Ye, L. Wang, Y. Zhang, S. Wang and W. Luo, "An Active Halide Catholyte Boosts the Extra Capacity for All-Solid-State Batteries," *Advanced Materials*, vol. 36, no. 33, p. , 2024.
- [6] N. Ding, S. W. Chien, T. L. D. Tam, X. Li, G. Wu, W. J. Lee, S. Y. Chiam, Y. S. Meng and D. W. H. Fam, "Revealing Phase Transitions in Poly(Ethylene Oxide)-Based Electrolyte for Room-Temperature Solid-State Batteries," *Advanced Energy Materials*, vol. , p. , 2024.
- [7] H. Kim, E. Jang, J. Cho, S. Pyo, H. Yun, J. Lee, B. Min, J. Han, J. Yoo and Y. S. Kim, "Strategic Atomic Interaction Modification for Highly Durable Inorganic Solid Electrolytes in Advanced All-Solid-State Li-Metal Batteries," *Small Structures*, vol. 5, no. 9, p. , 2024.
- [8] J. Sung, H. G. Lee, Y.-S. Jo, D. Kim, H. Park, J.-H. Park, D. Kim, Y.-C. Ha, K.-J. Baeg and J.-W. Park, "Size-Controlled Wet-Chemical Synthesis of Sulfide Superionic Conductors for High-Performance All-Solid-State Batteries," *Energy Storage Materials*, vol. 67, p. 103253, 2024.
- [9] J. Li, H. Tong, W. Zhou, J. Liu and X. Song, "Electrochemical Performance and Microstructure Evolution of A Quasi-Solid-State Lithium Battery Prepared By Spark Plasma Sintering," *ACS Applied Materials & Interfaces*, vol. 16, no. 6, p. 8045, 2024.
- [10] S. J. Mohammadi, S. A. M. Fashandi, S. Jafari and T. Nikolaidis, "A Scientometric Analysis and Critical Review of Gas Turbine Aero-Engines Control: From Whittle Engine to More-Electric Propulsion," *Measurement and Control*, vol. 54, no. 5-6, pp. 935-966, 2021.
- [11] A. Manthiram, "A Reflection on Lithium-Ion Battery Cathode Chemistry," *Nature Communications*, vol. 11, no. 1, p. , 2020.
- [12] W. Huang, X. Feng, X. Han, W. Zhang and F. Jiang, "Questions and Answers Relating to Lithium-Ion Battery Safety Issues," *Cell Reports Physical Science*, vol. 2, no. 1, p. 100285, 2021.

- [13] R. Bridgelall, "Aircraft Innovation Trends Enabling Advanced Air Mobility," *Inventions*, vol. 9, no. 4, p. 84, 2024.
- [14] B. Wu, S. Wang, W. J. E. Iv, Z. Deng, J. Yang and J. Xiao, "Interfacial Behaviours Between Lithium Ion Conductors and Electrode Materials in Various Battery Systems," *Journal of Materials Chemistry A*, vol. 4, no. 40, p. 15266, 2016.
- [15] A. Mills, S. Kalnaus, W.-Y. Tsai, Y.-F. Su, E. Williams, X. Zheng, S. Vaidyanathan, D. T. H. Jr, J. Nanda and G. Yang, "Elucidating Polymer Binder Entanglement in Freestanding Sulfide Solid-State Electrolyte Membranes," *ACS Energy Letters*, vol. 9, no. 6, pp. 2677-2684, 2024.
- [16] M. York, K. Larson, K. C. Harris, E. A. Carmona, P. Albertus, R. Sharma, M. Noked, E. Strauss, H. Ragones and D. Golodnitsky, "Recent Advances in Solid-State Beyond Lithium Batteries," *Journal of Solid State Electrochemistry*, vol. 26, no. 9, p. 1851, 2022.
- [17] P. Kumar, H. K. Channi, A. Babbar, R. Kumar, J. K. Bhutto, T. M. Y. Khan, A. Bhowmik, A. Razak and A. W. Wodajo, "A Systematic Review of Nanotechnology for Electric Vehicles Battery," *International Journal of Low-Carbon Technologies*, vol. 19, p. 747, 2024.
- [18] J. L. Pimlott, R. J. Street, M. P. Down and C. E. Banks, "Electrochemical Overview: A Summary of ACoxMnyNizO2 and Metal Oxides as Versatile Cathode Materials for Metal-Ion Batteries," *Advanced Functional Materials*, vol. 31, no. 51, p. 2107761, 2021.
- [19] Y. Kuang, C. Chen, D. J. Kirsch and L. Hu, "Thick Electrode Batteries: Principles, Opportunities, and Challenges," *Advanced Energy Materials*, vol. 9, no. 33, p. , 2019.
- [20] H. Liu, Q. Sun, Q. Zhang, J. Cheng, Y. Li, Z. Zeng, S. Zhang, X. Xu, F. Ji, D. Li, J. Lu and L. Ci, "The Application Road of Silicon-Based Anode in Lithium-Ion Batteries: From Liquid Electrolyte to Solid-State Electrolyte," *Energy Storage Materials*, vol. 55, p. 244, 2023.
- [21] T. Mageto, S. Bhoyate, F. M. D. Souza, K. Mensah-Darkwa, A. Kumar and R. K. Gupta, "Developing Practical Solid-State Rechargeable Li-Ion Batteries: Concepts, Challenges, and Improvement Strategies," *Journal of Energy Storage*, vol. 55, p. 105688, 2022.
- [22] Z. Hu, J. Li, B. Zhang and Y. Zhu, "Strategies to Improve the Performance of Li Metal Anode for Rechargeable Batteries," *Frontiers in Chemistry*, vol. 8, 2020.
- [23] M. Kim, J.-W. Park, B. G. Kim, Y.-J. Lee, Y.-C. Ha, S.-M. Lee and K.-J. Baeg, "Facile Fabrication of Solution-Processed Solid-Electrolytes for High-Energy-Density All-Solid-State-Batteries By Enhanced Interfacial Contact," *Scientific Reports*, vol. 10, no. 1, p. , 2020.
- [24] N. Xu, D. Zhang, M. Wang, X. Fan, T. Zhang, L. Peng, X.-D. Zhou and J. Qiao, "High-Performing Rechargeable/Flexible Zinc-Air Batteries By Coordinated Hierarchical Bi-Metallic Electrocatalyst and Heterostructure Anion Exchange Membrane," *Nano Energy*, vol. 65, p. 104021, 2019.
- [25] Z. Chen, K. Wang, P. Pei, Y. Zuo, M. Wei, H. Wang, P. Zhang and N. Shang, "Advances in Electrolyte Safety and Stability of Ion Batteries Under Extreme Conditions," *Nano Research*, vol. 16, no. 2, p. 2311, 2022.
- [26] D. Yu, J.-Y. Min, F. Lin and L. A. Madsen, "Mechanically and Thermally Robust Gel Electrolytes Built From A Charged Double Helical Polymer," *Advanced Materials*, vol. 36, no. 24, p. , 2024.

- [27] H. Shen, E. Yi, L. Cheng, M. Amores, G. Chen, S. W. Sofie and M. M. Doeff, "Solid-State Electrolyte Considerations for Electric Vehicle Batteries," *Sustainable Energy & Fuels*, vol. 3, no. 7, p. 1647, 2019.
- [28] J.-H. Lee, H. Lee, J. W. Lee, T. W. Kang, J. H. Park, J.-H. Shin, H. Lee, D. Majhi, S. U. Lee and J.-H. Kim, "Multicomponent Covalent Organic Framework Solid Electrolyte Allowing Effective Li-Ion Dissociation and Diffusion for All-Solid-State Batteries," *ACS Nano*, vol. 17, no. 17, p. 17372, 2023.
- [29] D. K. Singh, T. Fuchs, C. Krempaszky, B. Mogwitz and J. Janek, "Non-Linear Kinetics of the Lithium Metal Anode on Li6PS5Cl At High Current Density: Dendrite Growth and the Role of Lithium Microstructure on Creep," *Advanced Science*, vol. 10, no. 22, 2023.
- [30] V. Sharma, K. Singh and K. Narayanan, "A Review on Conventional to Bipolar Design of Anode Less All Solid-State Batteries," *Energy Advances*, vol. 3, no. 6, p. 1222, 2024.
- [31] W. Li, J. A. Quirk, M. Li, W. Xia, L. M. Morgan, W. Yin, M. Zheng, L. C. Gallington, Y. Ren, N. Zhu, G. King, R. Feng, R. Li, J. A. Dawson, T.-K. Sham and X. Sun, "Precise Tailoring of Lithium-Ion Transport for Ultralong-Cycling Dendrite-Free All-Solid-State Lithium Metal Batteries," *Advanced Materials*, vol. 36, no. 13, p. , 2023.
- [32] G. V. Alexander, C. Shi, J. S. O'Neill and E. D. Wachsman, "Extreme Lithium-Metal Cycling Enabled By A Mixed Ion- And Electron-Conducting Garnet Three-Dimensional Architecture," *Nature Materials*, vol. 22, no. 9, p. 1136, 2023.
- [33] A. A. Razali, S. N. Norazli, W. S. Sum, S. Y. Yeo, A. Dolfi and G. Srinivasan, "State-Of-The-Art of Solid-State Electrolytes on the Road Map of Solid-State Lithium Metal Batteries for E-Mobility," *ACS Sustainable Chemistry & Engineering*, vol. 11, no. 21, p. 7927, 2023.
- [34] H. J. Choi, D. W. Kang, J.-W. Park, J.-H. Park, Y. Lee, Y.-C. Ha, S.-M. Lee, S. Y. Yoon and B. G. Kim, "In Situ Formed Ag-Li Intermetallic Layer for Stable Cycling of All-Solid-State Lithium Batteries," *Advanced Science*, vol. 9, no. 1, p. , 2021.
- [35] H. Yang and N. Wu, "Ionic Conductivity and Ion Transport Mechanisms of Solid-State Lithium-Ion Battery Electrolytes: A Review," *Energy Science & Engineering*, vol. 10, no. 5, p. 1643, 2022.
- [36] R. Chen, Q. Li, X. Yu, L. Chen and H. Li, "Approaching Practically Accessible Solid-State Batteries: Stability Issues Related to Solid Electrolytes and Interfaces," *Chemical Reviews*, vol. 120, no. 14, p. 6820, 2019.
- [37] P. Swathi, S. O. V., T. Panneerselvam, R. Murugan and A. P. Ramaswamy, "Cross-Linked Polymer Composite Electrolyte Incorporated with Waste Seashell Based Nanofiller for Lithium Metal Batteries," *Energy & Fuels*, vol. 37, no. 8, p. 6186, 2023.
- [38] G. Zhao, X. Wang and M. Negnevitsky, "Connecting Battery Technologies for Electric Vehicles From Battery Materials to Management," *Iscience*, vol. 25, no. 2, p. 103744, 2022.
- [39] B. Ramasubramanian, G. K. Dalapati, M. V. Reddy, K. Zaghib, V. Chellappan and S. Ramakrishna, "Progress and Complexities in Metal-Air Battery Technology," *Energy Technology*, vol. 12, no. 5, p. , 2024.
- [40] J. Lee, C. Zhao, C. Wang, A. Chen, X. Sun, K. Amine and G.-L. Xu, "Bridging the Gap Between Academic Research and Industrial Development in Advanced All-Solid-State Lithium-Sulfur Batteries," *Chemical Society Reviews*, vol. 53, no. 10, p. 5264, 2024.

- [41] C. Huang, H. Zheng, N. Qin, C. Wang, L. Wang and J. Lu, "Single-Crystal Nickel-Rich Cathode Materials: Challenges and Strategies," *Acta Physico-Chimica Sinica*, vol. 40, no. 9, p. 2308051, 2024.
- [42] Y. Ma, R. Shang, Y. Liu, R. K. Lake, M. Ozkan and C. S. Ozkan, "Enabling Fast-Charging Capability for All-Solid-State Lithium-Ion Batteries," *Journal of Power Sources*, vol. 559, p. 232647, 2023.
- [43] R. Lin, Y. He, C. Wang, P. Zou, E. Hu, X.-Q. Yang, K. Xu and H. L. Xin, "Characterization of the Structure and Chemistry of the Solid-Electrolyte Interface By cryo-EM Leads to High-Performance Solid-State Li-Metal Batteries," *Nature Nanotechnology*, vol. 17, no. 7, p. 768, 2022.
- [44] C. Wang, Y. Zhao, Q. Sun, X. Li, Y. Liu, J. Liang, X. Li, X. Lin, R. Li, K. R. Adair, L. Zhang, R. Yang, S. Lu and X. Sun, "Stabilizing Interface Between Li₁₀SnP₂S₁₂ and Li Metal By Molecular Layer Deposition," *Nano Energy*, vol. 53, p. 168, 2018.
- [45] Y. Wang, R. Ni, X.-Z. Jiang, M. Yin, D. Zhang and Z. Xie, "An Electrochemical-Mechanical Coupled Multi-Scale Modeling Method and Full-Field Stress Distribution of Lithium-Ion Battery," *Applied Energy*, vol. 347, p. 121444, 2023.
- [46] R. Yang, Y. Xie, K. Li, W. Li, X. Hu, Y. Fan and Y. Zhang, "Thermal Characteristics of Solid-State Battery and Its Thermal Management System Based on Flat Heat Pipe," *Applied Thermal Engineering*, vol. 252, p. 123575, 2024.
- [47] M. Waseem, M. Ahmad, A. Parveen and M. Suhaib, "Battery Technologies and Functionality of Battery Management System for EVs: Current Status, Key Challenges, and Future Prospectives," *Journal of Power Sources*, vol. 580, p. 233349, 2023.
- [48] V. Iyer, J. C. Petersen, S. Geier and P. Wierach, "Development and Multifunctional Characterization of A Structural Sodium-Ion Battery using A High-Tensile-Strength Poly(Ethylene Oxide)-Based Matrix Composite," *ACS Applied Energy Materials*, vol. 7, no. 9, p. 3968, 2024.
- [49] R. Bridgelall and M. Corcoran, "Conformal Body Capacitors Suitable for Vehicles". United States of America Patent 9,966,790, 8 May 2018.
- [50] N. J. v. Eck and L. Waltman, "VOSviewer," Leiden University, 1 July 2024. [Online]. Available: vosviewer.com. [Accessed 30 June 2024].
- [51] Y. J. Nam, D. Y. Oh, S. H. Jung and Y. S. Jung, "Toward Practical All-Solid-State Lithium-Ion Batteries with High Energy Density and Safety: Comparative Study for Electrodes Fabricated By Dry- And Slurry-Mixing Processes," *Journal of Power Sources*, vol. 375, p. 93, 2017.
- [52] M. Yamamoto, Y. Terauchi, A. Sakuda and M. Takahashi, "Binder-Free Sheet-Type All-Solid-State Batteries with Enhanced Rate Capabilities and High Energy Densities," *Scientific Reports*, vol. 8, no. 1, p. , 2018.
- [53] J. Liang, Q. Sun, Y. Zhao, Y. Sun, C. Wang, W. Li, M. Li, D. Wang, X. Li, Y. Liu, K. R. Adair, R. Li, L. Zhang, R. Yang, S. Lu, H. Huang and X. Sun, "Stabilization of All-Solid-State Li-S Batteries with A Polymer-Ceramic Sandwich Electrolyte By Atomic Layer Deposition," *Journal of Materials Chemistry A*, vol. 6, no. 46, p. 23712, 2018.

- [54] Y. J. Choi, Y. J. Hwang, S.-I. Kim and T. Kim, "Performance Improvement of Argyrodite Solid Electrolyte for All-Solid-State Battery using Wet Process," *ACS Applied Energy Materials*, vol. 7, no. 10, p. 4421, 2024.
- [55] Y. Xu, J. Cui, B. Guo, Z. Li, W. Z. Wang and W. Li, "Cellulose-Based Eutectogel Electrolyte with High Ionic Conductivity for Solid-State Lithium-Ion Batteries," *Chemical Engineering Journal*, vol. , p. 151783, 2024.
- [56] W. Zhao, P. Tian, T. Gao, Y. Wang, C. Mu, H. Pang, J. Ye and G. Ning, "Different-Grain-Sizes Boehmite Nanoparticles for Stable All-Solid-State Lithium Metal Batteries," *Nanoscale*, vol. 16, no. 23, p. 11163, 2024.
- [57] C.-Y. Nam, H. Kim, W. Jin, J. H. Seol, T.-H. Kim, S.-Y. Yoon and S. Choi, "Improving the Stability of Ceramic-Type Lithium Tantalum Phosphate (LiTa2PO8) Solid Electrolytes in All-Solid-State Batteries," *Journal of Energy Storage*, vol. 80, p. 110254, 2024.
- [58] C. Y. Kwok, S. Xu, I. Kochetkov, L. Zhou and L. F. Nazar, "High-Performance All-Solid-State Li2S Batteries using An Interfacial Redox Mediator," *Energy & Environmental Science*, vol. 16, no. 2, p. 610, 2023.
- [59] Y. Shao, Y. Mei, T. Liu, Z. Li, Y. Zhang, S. Liu and Y. Liu, "Enhanced Electrochemical Stability and Ion Transfer Rate: A Polymer/Ceramic Composite Electrolyte for High-Performance All-Solid-State Lithium-Sulfur Batteries," *Journal of Colloid and Interface Science*, vol. 678, p. 682, 2024.
- [60] H. Cha, J. Yun, S. Kim, J. Kang, M. Cho, W. Cho and J.-W. Lee, "Stabilizing the Interface Between High-Ni Oxide Cathode and Li6PS5Cl for All-Solid-State Batteries Via Dual-Compatible Halides," *Journal of Power Sources*, vol. 617, p. 235157, 2024.
- [61] M. Terashima, K. Mamiya, T. Kimoto, S. Sasaki and S.-I. Iida, "Selection of Surface Coating Materials for Ni-Rich NCM in All-Solid-State Batteries Through Electronic Band Structure Analysis using UPS/LEIPS," *The Journal of Physical Chemistry C*, vol. 128, no. 22, p. 9393, 2024.
- [62] S. Liang, H. J. Yang, J. Hu, S. Kang, X. Zhang and Y. Fan, "Li7La3Zr2O12-Co-LiNbO3 Surface Modification Improves the Interface Stability Between Cathode and Sulfide Solid-State Electrolyte in All-Solid-State Batteries," *Membranes*, vol. 13, no. 2, p. 216, 2023.
- [63] H. Liu, X. Liu, L. Wang, L. Zhu and X. Zhang, "Evolution Process of the Interfacial Chemical Reaction in Ni-Rich Layered Cathodes for All-Solid-State Batteries," *ACS Applied Materials & Interfaces*, vol. , p. , 2023.
- [64] L. Guan, Y. Shi, C. Gao, T. Wang, J. Zhou and R. Cai, "Interfacial Contact Loss and Bending Effects on Electrochemical-Mechanical Modeling for All-Solid-State Li-Ion Batteries," *Electrochimica Acta*, vol. 440, p. 141669, 2022.
- [65] N. Tanibata, K. Matsunoshita, H. Takeuchi, S. Akatsuka, M. Koga, H. Takeda and M. Nakayama, "Fast Na-Diffusive Tin Alloy for All-Solid-State Na-Based Batteries," *Journal of Materials Chemistry A*, vol. 11, no. 47, p. 25859, 2023.
- [66] K. Heo, Y.-W. Song, D. Hwang, M. Kim, J.-Y. Hwang, J. Kim and J. Lim, "Effect of A Self-Assembling La2(Ni0.5Li0.5)O4 and Amorphous Garnet-Type Solid Electrolyte Composite on a Layered Cathode Material in All-Solid-State Batteries," *RSC Advances*, vol. 12, no. 22, p. 14209, 2022.

- [67] S. Saffirio, M. Falco, G. B. Appetecchi, F. Smeacetto and C. Gerbaldi, "Li_{1.4}Al_{0.4}Ge_{0.4}Ti_{1.4}(PO₄)₃ Promising NASICON-Structured Glass-Ceramic Electrolyte for All-Solid-State Li-Based Batteries: Unravelling the Effect of Diboron Trioxide," *Journal of the European Ceramic Society*, vol. 42, no. 3, p. 1023, 2021.
- [68] B. Zhao, W. Ma, B. Li, X. Hu, S. Lu, X. Liu, Y. Jiang and J. Zhang, "A Fast and Low-Cost Interface Modification Method to Achieve High-Performance Garnet-Based Solid-State Lithium Metal Batteries," *Nano Energy*, vol. 91, p. 106643, 2021.
- [69] Q.-C. Zhu, J. Ma, J. Huang, D. Mao and K.-X. Wang, "Realizing Long-Cycling Solid-State Li-CO₂ Batteries using Zn-Doped LATP Ceramic Electrolytes," *Chemical Engineering Journal*, vol. 482, p. 148977, 2024.
- [70] J. J. A. Kreissl, H. A. Dang, B. Mogwitz, M. Rohnke, D. Schröder and J. Janek, "Implementation of Different Conversion/Alloy Active Materials As Anodes for Lithium-Based Solid-State Batteries," *ACS Applied Materials & Interfaces*, vol. 16, no. 20, p. 26195, 2024.
- [71] B. Ma, R. Li, H. Zhu, T. Zhou, L. Lv, H. Zhang, S.-Q. Zhang, L. Chen, J. Wang, X. Xiao, T. Deng, L. Chen, C. Wang and X. Fan, "Stable Oxyhalide-Nitride Fast Ionic Conductors for All-Solid-State Li Metal Batteries," *Advanced Materials*, vol. , p. , 2024.
- [72] Z. Jiang, J. Yang, C. Liu, C. Wei, Z. Wu, Q. Luo, L. Zhang, X. Chen, L. Li, G. Li, S. Cheng and C. Yu, "Insights on Bi-O Dual-Doped Li₅PS₄Cl_{1.5} Electrolyte with Enhanced Electrochemical Properties for All-Solid-State Lithium Metal Batteries," *Nano Energy*, vol. , p. 109926, 2024.
- [73] J. Zhou, M. L. H. Chandrappa, S. Tan, S. Wang, C. Wu, H. Nguyen, C. Wang, H. Liu, S. Yu, Q. R. S. Miller, G. Hyun, J. Holoubek, J. Hong, Y. Xiao, C. Soulen, Z. Fan, E. E. Fullerton, C. Brooks, C. Wang, R. J. Clément, Y. Yao, E. Hu, S. P. Ong and P. Liu, "Healable and Conductive Sulfur Iodide for Solid-State Li-S Batteries," *Nature*, vol. 627, no. 8003, p. 301, 2024.
- [74] Y. Lu, H. Chang and K. P. Birke, "A Dual-Layered Anode Buffer Layer Structure for All Solid-State Batteries," *Batteries & Supercaps*, vol. , p. , 2024.
- [75] U.-H. Kim, T.-Y. Yu, J.-W. Lee, H. U. Lee, I. Belharouak, C. S. Yoon and Y.-K. Sun, "Microstructure- And Interface-Modified Ni-Rich Cathode for High-Energy-Density All-Solid-State Lithium Batteries," *ACS Energy Letters*, vol. 8, no. 1, p. 809, 2023.
- [76] B. Du, C. Shen, T. Wang and C. Sun, "A Flexible Solid-State Lithium Battery with Silver Nanowire/Lithium Composite Anode and V₂O₅ Nanowires Based Cathode," *Electrochimica Acta*, vol. 439, p. 141690, 2022.
- [77] S. C. Han, M. Ali, Y. J. Kim, J. Park, Y.-J. Lee, J.-W. Park, H. Park, G. Park, E. Lee, B. G. Kim and Y.-C. Ha, "Unraveling Electrochemo-Mechanical Aspects of Core-Shell Composite Cathode for Sulfide Based All-Solid-State Batteries," *Journal of Materials Chemistry A*, vol. 12, no. 37, p. 24896, 2024.
- [78] K. Lee and J. Sakamoto, "Li Stripping Behavior of Anode-Free Solid-State Batteries Under Intermittent-Current Discharge Conditions," *Advanced Energy Materials*, vol. 14, no. 17, p. , 2024.
- [79] N. Tanibata, N. Nonaka, K. Makino, H. Takeda and M. Nakayama, "Chloride Electrode Composed of Ubiquitous Elements for High-Energy-Density All-Solid-State Sodium-Ion Batteries," *Scientific Reports*, vol. 14, no. 1, p. , 2024.

- [80] Z. Xiong, Z. Wang, W. Zhou, Q. Liu, J.-F. Wu, T.-H. Liu, C. Xu and J. Liu, "4.2V Polymer All-Solid-State Lithium Batteries Enabled By High-Concentration PEO Solid Electrolytes," *Energy Storage Materials*, vol. 57, p. 171, 2023.
- [81] S. Poetke, Ş. Cangaz, F. Hippauf, S. Haufe, S. Dörfler, H. Althues and S. Kaskel, "Partially Lithiated Microscale Silicon Particles As Anode Material for High-Energy Solid-State Lithium-Ion Batteries," *Energy Technology*, vol. 11, no. 3, p. , 2023.
- [82] E. Hayakawa, H. Nakamura, S. Ohsaki and S. Watano, "Design of Active-Material/Solid-Electrolyte Composite Particles with Conductive Additives for All-Solid-State Lithium-Ion Batteries," *Journal of Power Sources*, vol. 555, p. 232379, 2022.
- [83] X. Xu, J. Cheng, Y. Li, X. Nie, L. Dai and L. Ci, "Li Metal-Free Rechargeable All-Solid-State Li₂S/Si Battery Based on Li₇P₃S₁₁ Electrolyte," *Journal of Solid State Electrochemistry*, vol. 23, no. 11, p. 3145, 2019.
- [84] A. I. P. Martinez, F. Aguesse, L. Otaegui, M. Schneider, A. Roters, A. Llordés and L. Buannic, "The Cathode Composition, A Key Player in the Success of Li-Metal Solid-State Batteries," *The Journal of Physical Chemistry C*, vol. 123, no. 6, p. 3270, 2019.
- [85] L. Wang, T. Wang, Y.-X. Yin, J.-L. Shi, C. Wang and Y.-G. Guo, "Exploiting Lithium-Depleted Cathode Materials for Solid-State Li Metal Batteries," *Advanced Energy Materials*, vol. 9, no. 28, p. , 2019.
- [86] G. Huang, J. Han, C. Yang, Z. Wang, T. Fujita, A. Hirata and M. Chen, "Graphene-Based Quasi-Solid-State Lithium-Oxygen Batteries with High Energy Efficiency and A Long Cycling Lifetime," *NPG Asia Materials*, vol. 10, no. 11, p. 1037, 2018.
- [87] L. Wach, Y. Khaydarov, P. Garkusha and R. Daub, "Establishing Laser Cutting of Components for Sulfide-Based Solid-State Batteries," *Journal of Laser Applications*, vol. 36, no. 4, p. , 2024.
- [88] S. Basak, J. Park, J. Jo, O. Camara, A. H. Tavabi, H. Tempel, H. Kungl, C. George, R. E. Dunin-Borkowski, J. Mayer and R.-A. Eichel, "Screening of Coatings for An All-Solid-State Battery using *in Situ* Transmission Electron Microscopy," *Journal of Visualized Experiments* , No., vol. 191, p. , 2023.
- [89] D. Cao, Y. Zhang, T. Ji and H. Zhu, "In Operando Neutron Imaging Characterizations of All-Solid-State Batteries," *MRS Bulletin*, vol. 48, no. 12, p. 1257, 2023.
- [90] K. Yoon, H. Kim, S.-W. Han, T.-S. Chan, K.-H. Ko, S. Jo, J. Park, S. Kim, S. Lee, J. Noh, W. Kim, J. Lim and K. Kang, "Detrimental Effect of High-Temperature Storage on Sulfide-Based All-Solid-State Batteries," *Applied Physics Reviews*, vol. 9, no. 3, p. , 2022.
- [91] Y.-W. Song, K. Heo, D. Hwang, M. Kim, H. Lee, B.-S. Kang, Y.-S. Hong, H.-S. Kim, J. Kim and J. Lim, "Influence of the Particle Size of the Ni-Rich Cathode Material on the Electrochemical Properties for All Solid-State Batteries," *Ionics*, vol. 28, no. 12, p. 5421, 2022.
- [92] S. Lou, N. Sun, F. Zhang, Q. Liu and J. Wang, "Tracking Battery Dynamics By Operando Synchrotron X-Ray Imaging: Operation From Liquid Electrolytes to Solid-State Electrolytes," *Accounts of Materials Research*, vol. 2, no. 12, p. 1177, 2021.
- [93] Z. Ge, X. Liu, X. Zou, Y. Zhan and Y. Luo, "Preparation and Properties of A Novel Green Solid Polymer Electrolyte for All-Solid-State Lithium Battery," *Journal of Applied Polymer Science*, vol. 138, no. 37, p. , 2021.

- [94] P. López-Aranguren, X. Judez, M. Chakir, M. Armand and L. Buannic, "High Voltage Solid State Batteries: Targeting High Energy Density with Polymer Composite Electrolytes," *Journal of the Electrochemical Society*, vol. 167, no. 2, p. 020548, 2020.
- [95] J. Zhang, C. Zheng, L. Li, Y. Xia, H. Huang, Y. Gan, C. Liang, X. He, X. Tao and W. Zhang, "Unraveling the Intra and Intercycle Interfacial Evolution of Li6PS5Cl-Based All-Solid-State Lithium Batteries," *Advanced Energy Materials*, vol. 10, no. 4, 2019.

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