

Review Article

Material-resolved patent landscape of all-solid-state battery electrolytes: technology evolution, collaboration networks, and commercialization implications

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ABSTRACT

All-solid-state batteries (ASSBs) are widely regarded as a promising pathway toward safer, higher-energy electrochemical storage for next-generation energy storage applications. However, limited quantitative evidence is available on how different solid electrolyte families are prioritized in real-world R&D portfolios. This study combines a structured review of solid electrolyte materials with a material-resolved patent analysis of 4328 patent families to map the global innovation landscape of ASSB electrolytes filed between 1999 and 2023. Patents were classified into seven subtypes: polymers, sulfides, oxides, sulfide–oxide hybrids, halides, hydrides, and polymer–inorganic hybrids. Guided by technology evolution and innovation-network perspectives, six hypotheses were examined concerning technological prioritization, platform transition, collaboration intensity, organizational composition, complementary platform emergence, and jurisdictional maturity. The results were consistent with all six hypotheses and indicated a pattern suggestive of sequential evolution, in which sulfide electrolytes have to date been the most prominent platform (45% of filings), while halides and polymer–inorganic hybrids appeared as fast-growing alternatives, indicating that the field may be diversifying rather than converging on a single platform. Collaboration-network analysis showed that 75% of leading hubs were centered on sulfide electrolytes and that firm and academia representation was balanced (50%–50%), suggesting a more balanced organizational structure than is often reported in emerging technology fields. From a commercialization perspective, the prominence of sulfide electrolytes suggests a continued need for controlled-atmosphere manufacturing and specialized processing infrastructure, whereas the growing visibility of halides and polymer–inorganic hybrids points to alternative development pathways with distinct manufacturing profiles. Overall, the findings indicate that ASSB commercialization strategies should consider not only electrochemical performance but also manufacturing requirements and application-specific needs.

1. Introduction

Rechargeable batteries are essential for electrified transportation, stationary energy storage systems, and portable electronics. Lithium-ion batteries (LIBs) currently dominate the secondary battery market owing to their high energy density, long cycle life, and high efficiency. However, with the rapid expansion of electric vehicle (EV) deployment and renewable energy integration, there is a growing demand for next-generation batteries capable of simultaneously achieving higher

energy densities, improved safety, and extended cycle life.

All-solid-state batteries (ASSBs) have emerged as a promising alternative to liquid-electrolyte LIBs. As flammable liquid electrolytes are replaced with non-flammable solid electrolytes in ASSBs, they provide improved thermal and mechanical stability. This configuration also enables the use of Li-metal anodes and high-voltage cathodes, thereby achieving substantially higher energy densities [1–3]. More importantly, solid-state electrolytes are regarded as key enablers of advanced Li-battery chemistries that are difficult to implement with flammable

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liquid electrolytes, including configurations employing Li-metal anodes coupled with high-voltage cathodes and other high-energy-density architectures [4]. Solid electrolytes also eliminate leakage and gas evolution while suppressing Li dendrite growth through their enhanced mechanical rigidity. Consequently, ASSBs are being pursued as next-generation power sources for EVs, grid-scale storage, and aerospace and military applications. Intensive research and development (R&D) and pilot-scale commercialization efforts are underway, led by global automakers, battery manufacturers, and public research institutions. Despite these performance advantages, the transition from laboratory research to commercial deployment remains constrained by challenges that differ across electrolyte families. Each platform involves distinct requirements in manufacturing infrastructure, processing conditions, and scalability, which influence development timelines and application suitability. For example, sulfide electrolytes offer high ionic conductivity and room-temperature processability but require controlled-atmosphere handling, whereas oxide electrolytes provide excellent stability but typically demand high-temperature sintering. These platform-specific characteristics shape not only cell-level performance but also broader commercialization pathways, including manufacturing scale-up and target application areas. Understanding how R&D resources are allocated across these platforms is therefore important for interpreting technology trajectories and commercialization priorities in the ASSB field.

The composition of the solid electrolyte is a critical determinant of ASSB performance. Solid electrolytes must satisfy stringent requirements for ionic conductivity, electrochemical stability, and interfacial compatibility [2,3,5,6]. Solid electrolytes can be classified into polymers, sulfides, oxides, halides, hydrides, sulfide–oxide hybrids, and polymer–inorganic hybrids, each with distinct advantages and drawbacks. These material-specific attributes directly influence commercialization pathways and therefore make it important to understand how R&D activity is distributed across electrolyte families. Although prior literature reviews have summarized scientific progress in ASSB electrolytes [1–3,5,6], they provide limited quantitative insight into how electrolyte families are prioritized in real-world R&D portfolios. Patent data offer a complementary perspective: patent filings reflect strategic resource allocation, whereas co-applications reveal underlying collaboration patterns [2,3]. To date, few patent-based studies have examined ASSBs at the level of specific electrolyte material families. R&D collaboration is increasingly recognized as an important mechanism for accelerating innovation in complex technological domains such as ASSBs [7,8]. Collaboration hubs and intermediary actors can help connect otherwise disconnected organizations and facilitate knowledge recombination [9,10]. Although recent patent analyses have examined battery production value chains and regional patenting trends, few studies have examined ASSB electrolytes from a combined perspective that integrates material-specific patenting patterns with collaboration network structures.

Against this background, this study examines six research questions informed by technology evolution and innovation-network perspectives. First, does ASSB electrolyte R&D follow a sequential trajectory from conductivity maximization to stability enhancement and then processability optimization, as reflected in changes over time in the patent shares of different electrolyte subtypes? Second, as the technology matures, do oxide electrolytes shift from a primary platform to a complementary or hybrid role, as indicated by a declining relative share despite continued growth in absolute filings? Third, is material-specific technical complexity positively associated with collaboration intensity, such that electrolyte families facing multiple technical challenges (e.g., sulfides) exhibit denser collaboration networks than those with fewer constraints? Fourth, does the organizational composition of collaboration hubs in the ASSB electrolyte network differ from the academia-dominated pattern often reported in emerging technology fields? If so, what features of ASSB electrolyte development may explain this difference? Fifth, do complementary platforms—specifically halides and

polymer–inorganic hybrids—expand rapidly once the limitations of the dominant platform become increasingly apparent? Sixth, does the concentration of national ASSB electrolyte patent portfolios across material subtypes reflect the technological maturity of each jurisdiction?

To address these questions, this study provides an integrated material-resolved assessment of global R&D activity in ASSB electrolytes based on a manually curated patent dataset. This study adopts an analytical review approach, integrating a structured synthesis of solid electrolyte families with empirical patent analysis. By linking qualitative domain knowledge to large-scale patent evidence, the approach provides a data-driven perspective on technological development. This study makes four major contributions to the literature. First, using a broad search strategy, a patent expert systematically screened retrieved records, developed a field-specific noise taxonomy for ASSB electrolyte patents, and identified valid patent families. This process documented typical sources of search noise for subsequent studies. Second, each valid patent family was classified into a detailed electrolyte subtype (polymer, sulfide, oxide, halide, sulfide–oxide hybrid, hydride, and polymer–inorganic hybrid) through full-text analysis of claims, examples, and technical descriptions rather than relying on pre-assigned classification fields. This approach enabled a material-resolved view of ASSB electrolyte technologies. Third, quantitative analyses of patent filings by electrolyte subtype—using both absolute counts and relative shares across five 5-year periods—were conducted to reveal shifts in material-specific R&D focus over time and to identify possible future development directions. In parallel, the electrolyte portfolios of leading global applicants were examined to identify their prioritized material families and to clarify how different material types were combined within individual R&D strategies. Fourth, a co-applicant-based collaboration network analysis identified major R&D collaboration hubs and quantified their technological intermediary roles. This analysis characterized their organizational composition (firm versus research institute) and collaboration scope (domestic versus international), and linked these collaboration strategies to the electrolyte materials on which the hubs focused. Taken together, these contributions provide a reproducible patent-based framework for mapping the technological landscape of ASSB electrolytes and supporting strategic planning for R&D and collaboration. Unlike previous ASSB patent studies that focused on battery trends or cell-production value chains [11], this work presents a material-resolved patent analysis by classifying patents into seven electrolyte subtypes, developing a reproducible noise taxonomy, and integrating these insights with collaboration-network analysis.

2. Solid electrolyte families and hypothesis development

This section briefly reviews the principal classes of solid electrolytes examined in this study and summarizes their key advantages and challenges in the context of ASSB commercialization. Various inorganic solid-state electrolytes—including sulfides, oxides, halides, and hydrides—as well as polymers and polymer–inorganic hybrid systems have been systematically investigated with respect to ion transport mechanisms, electrochemical stability, and design principles [12–14]. Wu et al. [14] compared the practical and theoretical performance limits of these electrolyte systems, highlighting the trade-offs between ionic conductivity, electrochemical stability, and processability in all-solid-state Li batteries. Building on these insights, the discussion below focuses on how material-specific properties shape R&D directions and motivate the material-resolved patent analysis presented in Sections 3 and 4.

In this study, solid electrolytes for ASSBs were categorized into seven subtypes based on their electrolyte chemistry and design rationale: polymers, sulfides, oxides, sulfide–oxide hybrids, halides, hydrides, and polymer–inorganic hybrids. The classification scheme defined in this study was applied consistently to both patent data and the literature review to ensure alignment between the background discussion and the subsequent statistical and network analyses.

2.1. Overview of solid electrolyte families

Seven solid electrolyte subtypes were considered in this study: polymers (AA), sulfides (BA), oxides (BB), sulfide–oxide hybrids (BC), halides (BD), hydrides (BE), and polymer–inorganic hybrids (CA). Table 1 summarizes the main advantages and challenges associated with each subtype. Detailed descriptions of material characteristics, ionic conductivity ranges, processing requirements, and interfacial behavior are provided in Supplementary Material S1. Briefly, sulfide electrolytes exhibit the highest ionic conductivity (10^{-3} – 10^{-2} S cm $^{-1}$) at room temperature but are prone to moisture sensitivity and H₂S evolution. Oxide electrolytes provide excellent electrochemical stability but typically require high-temperature sintering. Polymer electrolytes enable flexible, large-area processing yet display limited ionic conductivity at

Table 1

Advantages and key challenges of major solid electrolyte families considered in this study.

Electrolyte	Main advantages	Key challenges
Sulfide	• Very high Li⁺ conductivity • Low-temperature densification and good deformability • Excellent solid–solid contact, attractive for high-energy ASSBs	• Severe moisture sensitivity (H₂S generation) • Chemical/electrochemical instability at cathode and Li-metal interfaces • Mechanical brittleness and crack formation under stack pressure
Oxide	• Wide electrochemical stability window and high chemical robustness • Greater tolerance to air/moisture than sulfides • Potential stability against Li metal (e.g., garnet-type Li₇La₃Zr₂O₁₂ (LLZO))	• High-temperature sintering required for dense pellets, leading to higher cost • Large interfacial resistance with cathodes and Li metal • Grain-boundary resistance and difficulty in forming intimate solid–solid contact
Sulfide–oxide hybrid	• Combines high conductivity of sulfides with the chemical/mechanical stability of oxides • Improved environmental tolerance compared to that of pure sulfides • Possibility to engineer continuous ion-conduction pathways within reinforced frameworks	• Side reactions at sulfide/oxide interfaces • Complex microstructure control (particle size, dispersion, and volume fraction) • Property mismatch between phases can induce interfacial cracking and resistance growth
Halide	• High Li⁺ conductivity and good compatibility with high-voltage oxide cathodes • Better moisture tolerance than most sulfides, enabling milder processing conditions	• Limited mechanical strength and densification issues • Interfacial instability toward Li metal • Challenges in scalable synthesis of phase-pure materials
Hydride	• Very light elements, offering high gravimetric energy potential • Some compositions exhibit superionic conductivity at elevated temperatures • Abundant and low-cost raw materials	• Low ionic conductivity • Narrow electrochemical stability window and strong interfacial reactivity • High sensitivity to moisture/air, with gas-evolution risks
Polymer–inorganic hybrid	• Synergistic combination of polymer processability and inorganic conductivity/mechanical strength • Enhanced ionic conductivity compared to that of neat polymers; improved interfacial contact	• Need to engineer stable polymer–ceramic interfaces • Difficult trade-off between filler content, flexibility, and conductivity • Ensuring homogeneous dispersion and reproducible large-area fabrication

room temperature. Both sulfide–oxide and polymer–inorganic hybrid systems combine the advantages of their constituent phases while mitigating individual limitations. Halide and hydride electrolytes represent emerging alternatives with distinct properties. Beyond these single-phase families, mixed-anion electrolytes, such as halide-derived oxyhalides (e.g., chloride-derived oxychlorides), have recently emerged as a promising class of materials that may address cost and processing limitations of conventional halide electrolytes while retaining competitive ionic conductivity [15]. A dedicated, material-specific analysis of these emerging systems represents a valuable direction for future research.

2.2. Summary and link to the patent analysis

The diverse property profiles and technical challenges summarized in Table 1 underscore the need for a material-resolved view of ASSB R&D. Each electrolyte family presents distinct trade-offs between ionic conductivity, electrochemical stability, processability, and manufacturing complexity, thereby shaping differentiated R&D strategies across firms and jurisdictions. The following sections describe the construction and analysis of a global patent dataset that explicitly distinguishes between these electrolyte families.

2.3. Manufacturing and application considerations in ASSB electrolyte selection

The selection of solid electrolyte platforms is governed not only by electrochemical performance but also by manufacturing scalability, cost structures, and application-specific requirements. These factors critically influence commercialization pathways and strategic R&D prioritization.

Each electrolyte family presents distinct manufacturing profiles that shape scale-up feasibility. Sulfide electrolytes can generally be densified via cold-pressing at or near room temperature, which may enable high-throughput processing; however, their pronounced moisture sensitivity necessitates controlled-atmosphere facilities, adding to capital requirements [16,17]. Oxide electrolytes typically require high-temperature sintering, which limits throughput and may complicate co-processing with electrode materials [18]. Polymer and polymer–inorganic hybrid electrolytes are generally compatible with conventional coating and roll-to-roll techniques, potentially offering advantages for large-format cell production.

Performance requirements for solid electrolytes vary considerably depending on the target application. Electric vehicle applications generally prioritize high energy density and fast-charging capability, whereas grid-scale stationary storage emphasizes calendar life, round-trip efficiency, and system-level cost. Portable electronics may favor thin, flexible form factors over gravimetric energy density [19,20]. As a result, different electrolyte platforms may be better positioned for different use scenarios: sulfide-based systems are often discussed for high-energy automotive applications, polymer-based or hybrid systems for flexible form factors, and oxide-based systems for stationary applications where thermal robustness and long service life are prioritized.

Technology maturity levels vary across electrolyte families. Among the major platforms, sulfide-based systems appear to be closest to large-scale commercialization, as indicated by pilot-line activities and public roadmaps reported by several manufacturers. Oxide electrolytes, despite extensive research history, have seen limited commercial deployment primarily in thin-film micro-battery configurations. Halide electrolytes, while exhibiting promising properties, remain at earlier development stages. These maturity differences are reflected in the patent landscape analyzed in the following sections.

2.4. Theoretical framework and hypothesis development

Building on the material-specific characteristics reviewed above and

drawing on technology evolution and innovation network literature, six hypotheses (H1, H1-1, H2, H2-1, H3, H4) were developed to guide the subsequent patent analysis.

2.4.1. Technology evolution pattern

Technological evolution in complex material systems often follows a sequential pattern in which different performance attributes are prioritized at successive stages of development. In the early phase, R&D efforts typically focus on achieving threshold performance in the key functional parameter. Once this threshold is reached, attention shifts to secondary attributes, such as stability and manufacturability. For ASSB electrolytes, ionic conductivity constitutes the primary functional requirement; insufficient conductivity precludes practical cell operation, regardless of other properties. Accordingly, the following hypothesis was formulated:

H1. ASSB electrolyte R&D follows a “Conductivity → Stability → Processability” sequential prioritization pattern, reflected in changes over time in the distribution of patent families classified into different electrolyte subtypes.

As the technology matures and the limitations of the dominant platform become apparent, the materials initially pursued as primary alternatives may be repositioned as complementary components. Oxide electrolytes offer wide electrochemical stability windows and chemical robustness. However, they require high-temperature sintering and often exhibit large interfacial resistance. These characteristics make oxide materials more suitable as protective layers or hybrid components than as standalone electrolytes in manufacturing-oriented development. Accordingly, the following hypothesis was formulated:

H1-1. As ASSB technology advances toward commercialization, oxide electrolytes are gradually transitioning from a primary platform to a “functional complement.” This shift is evidenced by a declining share of oxide-based electrolyte patent families within the overall ASSB landscape, accompanied by their increasing integration into hybrid electrolyte systems designed to leverage complementary functionalities.

2.4.2. Collaboration intensity and technical complexity

Innovation network theory suggests that the complexity of technical challenges influences the structure and intensity of R&D collaboration [7,9]. Technologies that require the integration of multiple knowledge domains tend to exhibit denser collaboration networks, as no single institution can efficiently address all the relevant challenges. Sulfide electrolytes face multi-layered technical barriers including moisture sensitivity, interfacial instability, mechanical brittleness, and H₂S generation. These barriers span materials chemistry, process engineering, interfacial science, and cell design. Therefore, the following hypothesis was proposed:

H2. Material-specific technical complexity is positively associated with collaboration intensity, such that electrolyte families facing multi-layered challenges exhibit higher collaboration indices (CIs) and occupy more central positions in the co-applicant network.

Previous studies have consistently reported that universities and public research institutes serve as dominant technological intermediaries in emerging technology fields [9,21,22]. These institutions facilitate knowledge flow between otherwise disconnected actors. However, ASSB electrolyte development requires the simultaneous integration of material synthesis capabilities and manufacturing process expertise. These competencies are distributed across academic and industrial actors. Therefore, the following hypothesis was proposed:

H2-1. The organizational composition of collaboration hubs in ASSB electrolytes differs from the academia-dominated pattern typical of emerging technologies. Firms and academic institutions contribute more equally as technological intermediaries due to the dual-competency (materials + process) integration requirement.

2.4.3. Complementary platform emergence

Once a dominant platform is established and its limitations are widely recognized, R&D attention may shift toward alternative materials that address these shortcomings. Sulfide electrolytes exhibit pronounced moisture sensitivity and H₂S evolution risk. These limitations motivated the search for materials offering comparable conductivity with improved environmental tolerance. Halide electrolytes and polymer–inorganic hybrids directly address these constraints while maintaining reasonable ionic conductivity. Therefore, the following hypothesis was proposed:

H3. Complementary platforms (halides and polymer–inorganic hybrids) exhibit rapid growth following the consolidation of sulfides as the dominant platform. This growth is driven by recognition of sulfide-specific limitations.

2.4.4. Regional technology maturity

Patent portfolio compositions may reflect the technological maturity stages of different jurisdictions. During early-stage exploration, applicants pursue multiple material options in parallel. As technology matures and commercialization approaches, portfolios tend to converge on a smaller number of platforms that are perceived as the most viable. Therefore, the following hypothesis was proposed:

H4. The concentration of national patent portfolios reflects jurisdictional technology maturity. Converged portfolios (sulfide-dominated) indicate advanced development stages, whereas diversified portfolios suggest ongoing exploration.

These six hypotheses were tested using segmented trend analysis (H1, H1-1, H3, and H4) and collaboration network analysis (H2 and H2-1), as described in Section 3.

3. Data and methods

This section describes the data collection procedures and analytical methods employed in this study. First, irrelevant patent noise generated during the search for ASSB electrolytes was systematically identified and categorized. These records were then manually removed from the raw dataset. To the best of the authors' knowledge, prior patent analysis studies and industry reports have not documented a field-specific noise taxonomy for ASSB electrolyte patents. Next, an expert-driven, material-based classification scheme was developed for valid patents by reading the full specifications rather than relying on pre-existing classification fields. The following subsections describe each step of the analysis in detail, from data collection and cleaning to descriptive statistics, segmented trend analysis, and R&D collaboration network analysis.

3.1. Analysis framework

The overall analysis comprised four stages (Fig. 1). First, a clean

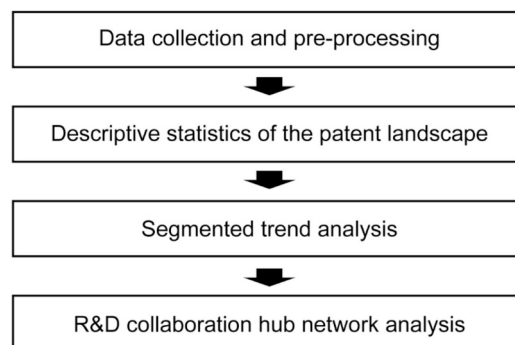


Fig. 1. Overview of the analysis framework for material-based patent classification and R&D collaboration network analysis of ASSB electrolytes.

dataset of valid ASSB electrolyte patents was constructed by applying a field-specific noise taxonomy and expert screening. Second, descriptive statistics were used to map the global patent landscape. Third, segmented trend analysis was conducted by electrolyte subtype. The 25-y observation period was divided into five 5-y segments to track changes in the relative patent share of each electrolyte subtype across time segments. Finally, R&D collaboration hub network analysis was performed based on co-applicant relationships to identify key technological intermediaries and to quantify their collaboration intensity. Together, these components provide a strategic evidence base for technology roadmapping and collaboration planning in ASSB electrolyte development.

After defining the patent search strategy and extracting raw data from the database, a dedicated pre-processing step was conducted to remove patents that were weakly related to ASSB electrolyte technologies. Each record in the raw dataset was manually reviewed by the first author, a registered patent attorney, and assigned either to the valid set or to one of several noise categories. This procedure enabled the development of a field-specific noise taxonomy for ASSB electrolyte patents. Patents classified as noise were excluded from further analysis, whereas the remaining documents were designated as valid patents. For each valid patent family, an electrolyte-specific technology code was assigned based on the actual material disclosed in the claims, examples, and descriptions. This procedure created a curated dataset that linked each invention to a well-defined electrolyte subtype. This curated dataset formed the basis for all subsequent analyses: (i) Descriptive statistics were used to examine annual filing trends, leading applicants, and jurisdictional distributions; (ii) A segmented trend analysis was performed to track absolute filing counts and relative filing shares for each electrolyte subtype across five 5-y periods; and (iii) An R&D collaboration hub network analysis was conducted to identify technological intermediaries from co-applicant relationships. The analysis further related technological intermediary roles to their primary electrolyte materials. All steps, including noise screening, material-based coding, and network construction, were conducted. Coding reliability was assessed through an independent review of a subset of classifications by a second coder (Section 3.2.4). This approach ensures that the analytical framework can serve as a reproducible reference for future patent-based studies on ASSB electrolytes.

The analytical framework was designed to test the six hypotheses developed in Section 2.4. Specifically, segmented trend analysis (Section 3.4) provides the empirical basis for evaluating H1 (sequential prioritization pattern), H1-1 (oxide repositioning), H3 (complementary platform emergence), and H4 (regional maturity differences). This analysis tracks absolute filing counts and relative filing shares across electrolyte subtypes and jurisdictions over five time segments. Collaboration network analysis (Section 3.5) tests H2 (complexity–collaboration relationship) and H2-1 (organizational composition of hubs). This analysis quantifies CIs, identifies material-specific hub distributions, and compares the firm–academia ratio among top collaboration hubs with patterns reported in prior studies of emerging technologies.

3.2. Data collection and pre-processing

The KeyWert database was used for patent searches and data extraction. According to the official description, KeyWert contains more than 300 million patent records, covers at least 15 major jurisdictions, and includes over 95% of global patent data. This coverage makes KeyWert suitable for capturing the global innovation landscape of ASSB electrolyte technology.

3.2.1. Patent family consolidation

A patent family is defined as a set of patent documents that claim the same priority and protect the same technical inventions across multiple jurisdictions. KeyWert provides a family consolidation function that extracts a representative record when a single invention has been filed in

several countries. In this study, patent families were consolidated on the basis of the EPO simple patent family (i.e., documents sharing exactly the same priority combination), as implemented in the KeyWert family-grouping function. Users can specify jurisdictional priority rules for consolidation, thereby enabling flexible analytical designs depending on the research objective. Researchers may choose whether to consolidate patent families based on whether duplicate inventions across jurisdictions are to be counted. Without consolidation, the absolute number of filings can be measured more precisely. However, the resulting statistics are heavily influenced by firms that file the same invention in multiple countries. This pattern reflects financial capacity rather than the underlying volume of distinct R&D outputs.

The present study aims to (i) examine both the absolute filing counts and relative filing shares by electrolyte subtype across time segments, (ii) anticipate future shifts in technology focus, and (iii) identify technological intermediaries at the level of distinct inventions. To align the statistics with R&D outputs rather than filing intensity alone, patent families were consolidated, and each family was treated as a single invention.

3.2.2. Patent search methodology

The patent search proceeded in three steps: (i) Selecting the target jurisdictions, (ii) Defining the filing and publication date (PD) ranges, and (iii) Designing the search keywords for ASSB electrolytes. The search scope was restricted to the five largest intellectual property offices (IP5) (comprising the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the United States Patent and Trademark Office (USPTO), and the China National Intellectual Property Administration (CNIPA)), and Patent Cooperation Treaty (PCT) filings. These offices account for the majority of global patenting activities, apply relatively stringent examination standards, and serve as primary routes for inventions with international commercial potential. The inclusion of PCT filings allowed the capture of inventions with broad geographic coverage that could potentially enter more than 150 jurisdictions. This approach reduced regional bias and ensured that the dataset reflected the core technological developments relevant to globally competitive R&D.

Patents with filing dates between January 1, 1999, and June 30, 2023, were included. PDs were considered up to December 31, 2024. Numerous patent-based technology studies use the year 2000 as a starting point to capture recent trends. The observation window was extended to 1999 in recognition of the common practice of filing patent applications approximately one year prior to the substantial completion of R&D. Given that patents are generally published approximately 18 months after filing, patents filed until mid-2023 provide a nearly complete view of the technologies disclosed toward the end of 2024. The reference date for data retrieval was March 28, 2025. To facilitate replicability, the upper bound of the PD was explicitly set to December 31, 2024, considering both the update cycles of national patent offices and the data-refresh schedule of KeyWert. The search database and temporal scope are listed in Table 2.

A search query was designed to capture ASSB electrolyte patents by using the broadest possible electrolyte-related expressions. Specifically, the search targeted patents with titles referring to “all-solid-state battery” or “all-solid-state electrolyte,” thereby including both cell- and electrolyte-focused inventions. This title-only search strategy inevitably reduces recall to some extent but substantially constrains noise from broader text fields. This drawback was partially compensated for through manual screening of all retrieved records and by explicitly treating potentially missed cases as a limitation of the study. Even with a title-restricted query explicitly targeting all-solid-state electrolyte terms, the retrieved set still contained substantial noise (as documented in the noise taxonomy, Section 3.2.3). Expanding the query to title, abstract, and claims (TAC) would greatly increase the dataset size, making expert-level screening and full-text material classification infeasible under the case-by-case approach used here. Importantly, characterizing noise even

Table 2
Search database and scope of analysis.

Data type	Jurisdictions	Database	Analysis period	Search scope
Published and granted patent documents	Korea (KR) United States (US) Japan (JP) Europe (EP) China (CN) PCT	KeyWert	Filing date (Application date (AD)): 1 Jan 1999–30 Jun 2023 & PD: up to 31 Dec 2024	Search field: patent title; screening and classification: full text (title, abstract, claims, and description)

under a tightly constrained title query is itself an objective of this study, as it supports the design of future TAC-based queries that improve recall while systematically excluding the noise patterns identified in this work. An alternative strategy, i.e., constructing separate keyword sets for each electrolyte subtype, was rejected because the terminology for specific electrolyte materials (e.g., sulfides, oxides, hybrids) overlaps substantially. Such overlap would lead to duplicate counting of the same patent family across multiple sub-datasets. To avoid this issue, a single comprehensive raw dataset of ASSB electrolyte-related patents was first collected. Electrolyte subtypes were subsequently differentiated through expert reading and manual coding. In total, the raw dataset contained 684 patent families filed at the KIPO, 1138 at the USPTO, 2451 at the JPO, 36 at the EPO, 2686 at the CNIPA, and 1649 under the World Intellectual Property Organization (WIPO)–PCT system (Table 3).

3.2.3. Noise identification and categorization

Title-based patent searches using terms such as “all-solid-state battery” and “all-solid-state electrolyte” retrieved a large number of irrelevant records. Because the reliability of patent-based analysis depends strongly on dataset quality, the retrieved records were systematically screened for search-related noise. An expert patent attorney manually reviewed each record in the raw dataset and assigned it either to the valid set or to one of 17 predefined noise categories (N1–N17). Classification was conducted using predefined exclusion criteria based on the patent title, claims, and embodiments, and borderline cases were resolved through full-text review. The exclusion criteria for each category are summarized in Table 4. The reliability of the subtype classification was assessed through an independent re-classification of a stratified random sample, as detailed in Section 3.2.4.

For example, category N3 included Na-ion, Al-ion, or Mg-ion battery patents whose titles referred to “all-solid-state batteries,” but whose claims and embodiments described only non-Li-ion chemistries and did not disclose Li-based solid electrolyte compositions. These records were therefore excluded from the valid ASSB electrolyte set. Among the noise categories, N9 accounted for the largest number of records (2451 cases). Patents assigned to N9 were related to batteries, electrodes, or manufacturing methods for solid batteries, but did not claim or describe solid electrolyte compositions in technical detail. These records were excluded from the valid dataset but retained within the noise taxonomy to document common search errors in this field. From the 8644 patent

Table 3
Search query and raw patent counts by jurisdiction.

Technology domain	Search query (KeyWert syntax)	Raw dataset
ASSB electrolytes	TI:((all N/1 solid*) OR (solid* N/1 state*)) AND (batter* OR cell OR electrolyte*) AND AD:(19990101–20,230,630) AND PD:(≤20241231)	KIPO (KR) 684
		USPTO (US) 1138
		JPO (JP) 2451
		EPO (EP) 36
		CNIPA (CN) 2686
		WIPO (PCT) 1649
		Total 8644

Table 4
Noise categories (N1–N17) with exclusion criteria.

Noise category	Exclusion criterion (reason for removal)	No. of patent families
N1	Unrelated to solid electrolytes; generic use of “solid-state” or “solid-state battery” only	165
N2	Fuel-cell or fuel-cell battery technologies	115
N3	Non-Li-ion metal secondary batteries (e.g. Na-ion, Al-ion, Mg-ion)	143
N4	Manufacturing equipment for solid batteries or devices using solid batteries, without electrolyte composition details	191
N5	Battery management and electric-vehicle control systems	22
N6	ASSB cell stacking or structural designs without specific solid-electrolyte features	371
N7	Capacitors and related devices	463
N8	Solar cells, photovoltaic batteries, and other non-Li-ion cells	106
N9	Manufacture of batteries, electrodes, or solid cells without the technical features of solid electrolytes	2451
N10	Semiconductor devices without the technical features of solid electrolytes	14
N11	Coating compositions and physical/chemical mixing or dispersion processes for flowable materials	24
N12	Battery additives, binder technologies, and organic polymer products without solid-electrolyte features	91
N13	Genetic engineering technologies	16
N14	Physical/chemical analysis of materials and digital data-processing methods	42
N15	Electrical/telecommunication technologies and conductive objects	40
N16	Semi-solid batteries, liquid electrolytes, and their fabrication methods	33
N17	Zn-ion, Zn–S, and Zn–air batteries	29
Total		4316

families in the raw dataset, 4316 were identified as noise and excluded, resulting in 4328 valid ASSB electrolyte patent families for subsequent analysis (Fig. 2).

3.2.4. Valid patent selection and data pre-processing

After noise filtering, the valid patents were organized using a three-level material classification scheme. At the primary level, all records were grouped under all-solid-state electrolytes. At the intermediate level, patents were classified into organic (A), inorganic (B), and organic–inorganic hybrid (C) electrolytes. At the detailed level, these intermediate classes were further divided into seven electrolyte subtypes. Table 5 summarizes the number of valid patents in each subtype, and Table 6 lists representative compositions for each category.

Classification was based on expert review of the full patent text rather than on IPC codes or other pre-assigned metadata fields. The independent claims were examined first. When the electrolyte material could not be clearly identified from the claims alone, the experimental examples were consulted. For patents without experimental examples, the detailed description was reviewed to identify the technical problem addressed and the electrolyte material disclosed. Through this iterative review process, the subtype definitions were refined and applied

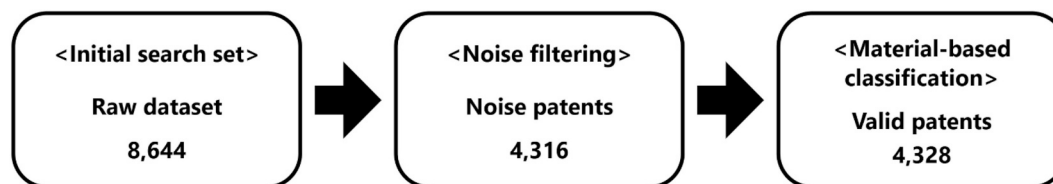


Fig. 2. Workflow from initial search results to noise removal and technology classification. Numbers indicate patent families.

Table 5

Technology categories and valid patent counts.

Primary level	Intermediate level	Subtype	Valid patent counts
ASSB electrolytes	Organic (A)	Polymer (AA)	530
		Sulfide (BA)	1965
	Inorganic (B)	Oxide (BB)	1393
		Hybrid (Sulfide + Oxide) (BC)	25
		Halide (BD)	66
		Hydride (BE)	11
		Hybrid (Organic + Inorganic) (CA)	338
	Organic + Inorganic (C)		
	Total (valid patent counts)		4328

Table 6

Representative electrolyte compositions by subtype.

Subtype	Representative Material Subclasses
Polymer (AA)	PEO, PA, PAM, PAN, PVDF-HFP, PMMA, PTFE, PVA, PI, PS, PE, PEG, PEGDA, PEGMA, PES, PC, PCL, PBMA, PVP, PVF
Sulfide (BA)	LGPS, LPS, argyrodite-type, thio-LISICON-type, additive/doped compositions
Oxide (BB)	Garnet, perovskite, NASICON, LiPON, glass-type families
Hybrid Sulfide + Oxide (BC)	Sulfide + oxide composites
Halide (BD)	LiInClF, Li ₃ AlF ₆ , Li ₂ ZrCl ₆ , Li ₃ YCl ₆ , Li ₂ ZrF ₆ , Li ₃ InCl ₆ , Li ₃ YBr ₆ , Li ₃ ErCl ₆ , Li ₃ ScCl ₆ , Li ₃ HoCl ₆ , Li ₃ TbCl ₆
Hydride (BE)	LiH, LiBH ₄ , LiCB ₃ H ₁₀ , Li ₂ B ₁₂ H ₁₂ , LiBH ₄
Hybrid Polymer + Inorganic (CA)	Polymer + sulfide, polymer + oxide

consistently across the valid patent set, after which all records were assigned to one of the seven subtypes summarized in Tables 5 and 6. Ambiguous cases were resolved using the same full-text review principles described in Section 3.2.3. Under this single-label scheme, mixed-anion or multiphase inorganic systems (e.g., oxyhalide or halide–oxide combinations) were not defined as separate subtypes and were classified according to their dominant Li⁺-conducting phase within the seven-category framework.

In applying this rule, additives, dopants, coatings, protective layers, and electrode materials were excluded from subtype assignment, whereas doping or halogen substitution within a single family was retained (e.g., halogen-doped argyrodite remained classified as a sulfide). Deliberate combinations of two inorganic electrolyte families were coded as sulfide–oxide hybrids (BC), while polymers combined with any inorganic electrolyte were classified as polymer–inorganic hybrids (CA). Finer subdivision of inorganic hybrids was not pursued, as the only defined hybrid category (sulfide–oxide) contains only a small number of families, suggesting that additional subdivisions would not yield statistically meaningful groups.

The classification described above was performed by the first author. To assess its reliability independently of this single expert, an inter-rater agreement test was conducted. A stratified random sample of 291 valid patent families – drawn with fixed-seed random sampling, with the low-frequency subtypes (hydride, sulfide–oxide hybrid, and halide) over-sampled to ensure adequate coverage – was independently re-classified by an experienced patent analyst (B.S. in chemical engineering, with over 100 completed patent analysis projects) from the same patent firm who was not an author of this study and was blinded to the original classification. The second coder applied the same codebook and single-label rule without access to the original labels. Agreement between the two classifications was almost perfect: the exact agreement was 97.6% (284/291) and Cohen's κ was 0.97 (95% CI, 0.95–0.99); when re-weighted to the full-population subtype distribution to account for the stratified design, κ remained 0.95. Per-subtype agreement was 100% for the hydride, sulfide–oxide hybrid, halide, and polymer–inorganic hybrid families, and ranged from 94.0% to 98.5% for the polymer, oxide, and sulfide families. All seven disagreements occurred at the boundary between single-phase and composite/hybrid classifications (e.g., polymer vs. polymer–inorganic hybrid; oxide or sulfide vs. sulfide–oxide hybrid); these were resolved by discussion, and the final labels followed the original expert classification.

3.3. Descriptive statistics of the patent landscape

Using the valid patent dataset, descriptive analyses were first conducted. Specifically, the following aspects were examined: (i) Annual patent filings and country-level shares of total patent filings, (ii) Patent filings across jurisdictions, (iii) Leading applicants and the distribution of their jurisdictional filings, and (iv) Leading applicants and their filing distribution by electrolyte subtype. Additionally, forward-citation statistics were compiled for each electrolyte subtype, including the mean, median, proportion of families cited at least once, and an age-normalized metric (citations per year since filing) to account for differences in citation accrual time (Table 7). The most frequently cited representative family within each subtype is also reported (Table S1). Forward citations are interpreted as a proxy for technological influence, reflecting the extent to which subsequent filings build upon prior knowledge, but they do not indicate validated cell performance or commercialization readiness. While sulfide families are the most numerous, their mean citation counts are comparable to those of oxide, polymer, and polymer–inorganic hybrid families. After age normalization, halide families reach citation rates similar to sulfides, indicating that filing volume alone does not fully capture technological influence across subtypes.

3.4. Segmented trend analysis

To capture medium-term shifts in patenting activity, segmented trend analysis was performed using the valid patent dataset. The objective of this study is to provide a decision-support tool for R&D planning by tracking changes in patent filings for each electrolyte subtype and using these temporal patterns to infer future development priorities. Recognizing that the timing of patent filing does not coincide exactly with the completion of the underlying R&D, 5-y time segments were adopted to smooth short-term fluctuations and capture meaningful

Table 7

Forward-citation statistics of valid patent families by electrolyte subtype.

Subtype	n	Total	Mean	Median	Max	% cited	Citations / year [†]
Sulfide (BA)	1965	5429	2.76	0	337	34%	0.36
Oxide (BB)	1393	4510	3.24	0	76	43%	0.42
Polymer (AA)	530	1713	3.23	1	67	57%	0.53
Polymer–inorganic hybrid (CA)	338	1584	4.69	1	59	60%	0.79
Halide (BD)	66	87	1.32	0	23	35%	0.38
Sulfide–oxide hybrid (BC)	25	33	1.32	0	14	24%	0.18
Hydride (BE)	11	14	1.27	0	10	36%	0.24

* Forward citations are used as a proxy for technological influence and do not represent validated cell performance or commercialization readiness. The citation distribution is highly skewed (a small number of families accumulate most citations), so the median and the percentage of families cited at least once are reported alongside the mean.

[†] Because earlier-filed families have had more time to accrue citations, the age-normalized measure (citations per year since filing, reference year 2024) is also reported to enable a fairer cross-subtype comparison. Notably, although sulfide families are the most numerous, their mean citation count (2.76) does not exceed that of oxide (3.24), polymer (3.23), or polymer–inorganic hybrid (4.69) families; and after age normalization the recently emerging halide families (0.38) reach a per-year citation rate comparable to that of sulfides (0.36), indicating that filing volume alone does not capture technological influence across subtypes.

shifts in patenting activity. Typically, an initial patent is filed during the early conceptual phase, followed by incremental patent filings as the technology is refined. These subsequent filings may be submitted by the original applicant or by competitors building upon the disclosed invention. Accordingly, as shown in Table 8, five segments were defined: Segment 1 (1999-01-01 to 2003-12-31), Segment 2 (2004-01-01 to 2008-12-31), Segment 3 (2009-01-01 to 2013-12-31), Segment 4 (2014-01-01 to 2018-12-31), and Segment 5 (2019-01-01 to 2023-12-31).

For each segment, the absolute number of filings for each electrolyte subtype was first calculated to quantify the total R&D output for each material system. The relative filing share of each subtype was then derived by setting the total number of patents within a given segment to 100 and computing the proportion attributable to each electrolyte category. This procedure allowed segment-level results to be interpreted as proportional allocations of patenting activity rather than raw filing volumes. Focusing solely on absolute filing counts would primarily confirm that ASSB patenting has increased over time. In contrast, the relative filing share of each electrolyte subtype within each time segment reveals how the distribution of R&D efforts across electrolyte materials has evolved. These proportional changes provide a basis for anticipating future shifts in R&D focus.

The relative filing share of subtype i in segment t was defined as $s(i,t) = n(i,t) / \sum_i n(i,t)$. Changes in the subtype composition across the five segments were tested with χ^2 test of independence on the subtype $\times$ segment contingency table (with a Monte Carlo estimate of the p -value to accommodate low-frequency subtypes). Monotonic trends in the relative share of each subtype were assessed using the Cochran–Armitage trend test with segment scores 1–5. Jurisdictional portfolio concentration was quantified using the Herfindahl–Hirschman Index, $HHI_j = \sum_i [p(i,j)]^2$, where $p(i,j)$ is the share of subtype i within jurisdiction j .

In addition, to provide direct evidence for the repositioning of oxide electrolytes (H1-1), the oxide (BB) patents in Segments 3–5 were further sub-coded according to the functional role of the oxide. Based on the abstract and the independent claim of each patent, the oxide was classified as either a standalone/bulk electrolyte (S) or a complementary component such as a protective layer, coating, or composite constituent (C); patents whose functional role could not be determined at this level – requiring examination of the embodiments – were labeled unclear (U) and excluded from the proportional analysis. This sub-coding was

Table 8

Time segmentation for patent trend analysis.

Segment	Period	Filing Date
Segment 1	Years 1–5	January 1, 1999–December 31, 2003
Segment 2	Years 6–10	January 1, 2004–December 31, 2008
Segment 3	Years 11–15	January 1, 2009–December 31, 2013
Segment 4	Years 16–20	January 1, 2014–December 31, 2018
Segment 5	Years 21–25	January 1, 2019–December 31, 2023

performed with the assistance of a large language model (Gemini 3.1 Pro, Google) and spot-checked by the first author, a registered patent attorney. The complementary share (C among S + C) was then compared across segments and tested for a monotonic trend using the Cochran–Armitage test defined above.

3.5. R&D collaboration hub network analysis

For the collaborative network analysis, 524 patents were selected from the total set of 4328 valid patents. These documents were jointly filed by two or more distinct applicants and were thus suitable for constructing an institution-level collaboration network based on co-applicant relationships. In this study, the CI of an institution is defined as the number of distinct co-applicant partner institutions with which it jointly filed one or more patent families during the observation period; this quantity corresponds to the degree centrality of the institution in the co-applicant network. An institution with a higher CI therefore collaborates with a greater number of distinct partners and occupies a more central position in the R&D collaboration network. To characterize collaboration roles beyond the number of direct partners, we additionally computed two normalized centrality measures: betweenness centrality, which captures the extent to which an institution bridges otherwise weakly connected parts of the network, and eigenvector centrality, which captures the extent to which an institution is connected to other highly connected institutions. These measures were computed on the full, entity-resolved co-applicant network (308 nodes, 321 edges, and 77 connected components), with edge weights given by the number of co-filed patent families between each pair of institutions. Because the network is highly fragmented, eigenvector centrality concentrates on the most densely interconnected component and is near zero for institutions outside it; we therefore interpret degree (CI) and betweenness centrality as the primary measures, with eigenvector centrality reported as a complementary indicator. The values for the top-20 hubs are reported in Table S4. During data pre-processing, the institutional names were standardized using artificial intelligence-based similarity-matching algorithms. The results were subsequently verified manually by an expert patent attorney to ensure accuracy. Entity resolution was performed through a combined approach that employed hierarchical clustering and natural language processing techniques to merge institution names with high lexical and semantic similarity. In ambiguous cases, additional rule-based heuristics were applied to improve classification precision.

In constructing the network topology, institutions with high centrality metrics were defined as hub nodes, whereas their co-applicants were designated as peripheral nodes. Node sizes were scaled in proportion to the number of jointly filed patent families between institutions. To maintain visual clarity, only representative peripheral nodes were displayed for each hub. Multi-hub intermediary institutions

were highlighted to explicitly indicate their bridging roles. This design enabled the identification of not only major hubs but also technological intermediaries that connect otherwise separate institutional clusters. In the following section, these CIs are interpreted together with the electrolyte subtype distribution of patent families associated with each hub to examine how electrolyte-specific technical challenges shape R&D collaboration structures.

4. Results and discussion

This section presents and discusses the main empirical findings from the patent analysis, with particular attention given to how material-specific innovation patterns and R&D collaboration structures shape the emerging landscape of ASSB electrolytes.

4.1. Descriptive statistics

4.1.1. Annual patent filings and country-level share

The annual number of patent families for ASSB electrolytes from 1999 to 2023, by filing year is presented in Fig. 3. The filing year serves as the temporal reference for describing the historical evolution of patenting activity. Patent filings exhibit a clear upward trajectory over the entire period, with pronounced surges in 2006, 2011, 2015, 2018, and 2021. These spikes correspond to periods during which firms and research institutions intensified their efforts to secure intellectual property in anticipation of future commercialization. The overall pattern confirms that ASSB electrolytes have evolved from an emerging and relatively specialized topic to a strategically significant field within the global battery R&D landscape. To illustrate how leading firms have recently positioned themselves, the filings of the two most active applicants in 2022 were examined. Toyota Motor Corporation filed 70 patent families, mainly on sulfide-based electrolytes targeting low-cost, high-productivity manufacturing, as well as improved resistance to internal short-circuit formation. Samsung SDI filed 38 patent families, focusing on high-capacity and long-cycle sulfide electrolytes, including $\text{Li}_6\text{PS}_5\text{Cl}$ and related argyrodite-type compositions. These examples reveal that sulfide electrolytes occupy a central position in current industrial R&D strategies.

4.1.2. Leading applicants and jurisdictional filing patterns

The filing activity of the top 10 applicants in ASSB electrolyte technologies is presented in Fig. 4. Notably, all of these applicants are headquartered in JP or KR, underscoring the central role of these two

countries in shaping global R&D on solid-state electrolytes. Toyota Motor Corporation ranks first, with 633 patent families related to solid-state battery technologies. Its filings are concentrated in Japan (approximately 400 families), followed by the US and filings under the PCT route. This distribution indicates a strategy that combines strong protection of core technologies in the domestic market with selective coverage of major overseas markets. The portfolio of Toyota Motor emphasizes sulfide and halide electrolytes, as well as Li-metal-compatible cell architecture, consistent with its publicly announced ASSB commercialization plans. Samsung Electronics Co., Ltd. (Samsung Electronics, KR) ranked second with 134 patent families, driven by internal R&D on solid-state cell architecture and interfacial engineering. Its strong presence in the US indicates that the US is regarded as the primary target market for advanced battery technologies. Fujifilm Corporation (JP) follows with 130 patent families, focusing on polymer binders and interfacial stabilization technologies for solid-state batteries, and exhibits high filing intensity under the PCT route. Korean applicants such as Samsung Electronics, Samsung SDI, LG Energy Solution, Ltd., Hyundai Motor Company, and LG Chem, Ltd., collectively account for a substantial share of global ASSB-related filings. Their coordinated activity reflects a strategic effort to maintain technological leadership in next-generation batteries and to strengthen competitiveness in both the domestic and global EV markets.

4.1.3. Leading applicants by electrolyte subtype

The relative distribution of electrolyte subtypes in the portfolios of the top ten applicants is shown in Fig. 5. For each applicant, the number of valid patent families in each electrolyte category is converted into a percentage share, revealing the principal technological research directions within the corresponding R&D strategies.

Toyota Motor focuses predominantly on sulfide electrolytes, especially Li_2S - P_2S_5 -based compositions with halide (Cl and Br) additives to enhance ionic conductivity and stability. Samsung Electronics also emphasizes Li_2S - P_2S_5 -based sulfides combined with interface-stabilizing additives and coatings, while maintaining an active oxide-electrolyte program centered on LLZO-family garnets. The portfolio of Fujifilm Corporation is dominated by polymer-inorganic hybrid electrolytes that combine polymer matrices with inorganic solid electrolytes to simultaneously improve mechanical flexibility, ionic conductivity, and interfacial adhesion. Samsung SDI primarily develops diverse sulfide compositions using Li_2S and related Li sulfides (e.g., LiAlS_2 and LiBiS_2), indicating broad exploration of sulfide-based material space. Murata Manufacturing Co., Ltd. (JP) and Taiyo Yuden Co., Ltd. (JP) concentrate

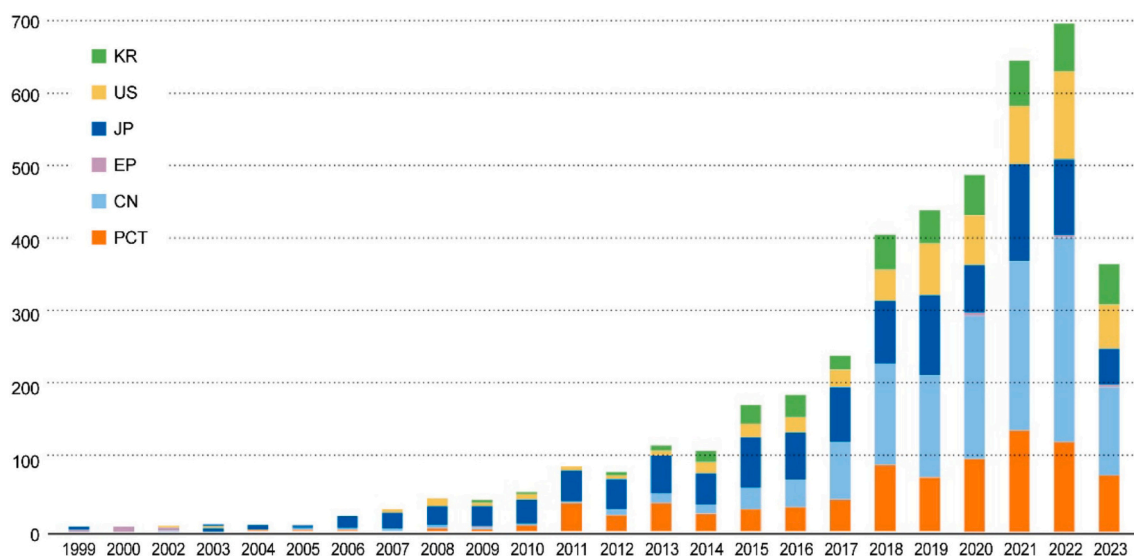


Fig. 3. Annual number of patent families related to ASSB electrolyte technologies by filing year (1999–2023).

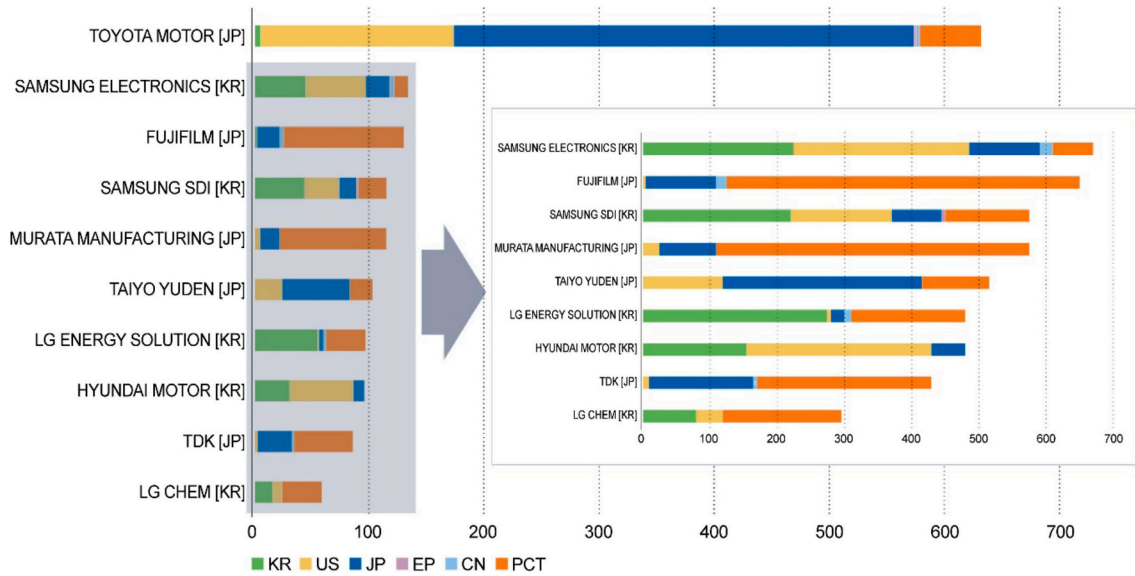


Fig. 4. Filing activity of the main institutional players in ASSB electrolyte technologies.

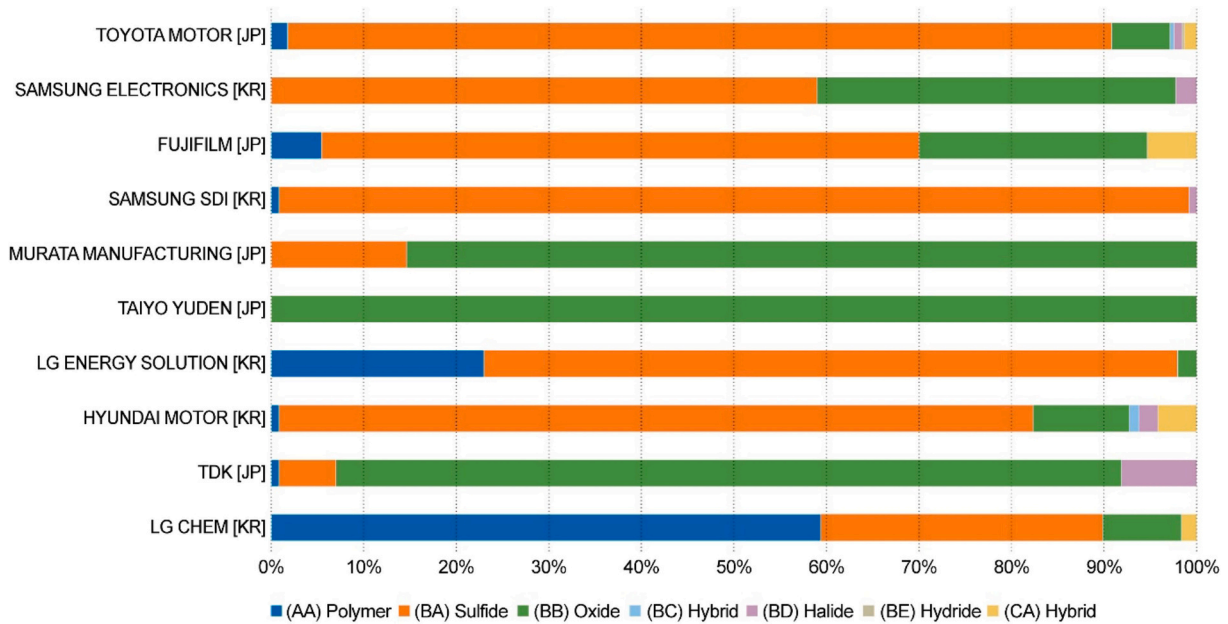


Fig. 5. Relative distribution of electrolyte subtypes in the portfolios of the top ten applicants.

primarily on oxide electrolytes. Murata develops garnet and Li superionic conductor (LISICON)-type oxides, whereas Taiyo Yuden emphasizes sodium superionic conductor (NASICON)-type oxides and multi-layer oxide architectures. In the corresponding valid patent families, both firms integrate these materials into compact multi-layer cell designs. LG Energy Solution focuses on LGPS-based sulfides incorporating elements such as Sn and Si. The related valid patent families indicate efforts to combine high ionic conductivity with improved electrochemical stability. Hyundai Motor developed polymer-sulfide hybrid electrolytes to enhance ionic conductivity and overall stability, while TDK Corporation (JP) worked on metal-doped oxide electrolytes and halide systems to simultaneously improve conductivity and cell performance. LG Chem showed relatively strong patenting activity in polymer electrolytes.

Taken together, these subtype-level patterns of valid patent families indicate that: (i) non-sulfide-focused strategies are mainly pursued by

Murata and Taiyo Yuden (oxide electrolytes) and LG Chem (polymer electrolytes); (ii) LG Energy Solution and LG Chem exhibit patenting activities across both sulfide and polymer electrolyte systems; (iii) polymer-inorganic hybrids account for a comparatively larger share of patent families in the portfolios of Fujifilm Corporation and Hyundai Motor; (iv) halide electrolytes are most frequently represented in the valid patent families of TDK Corporation, Samsung Electronics, and Hyundai Motor; and (v) sulfide-oxide hybrids, while still limited in absolute filing counts, appear in the portfolios of Hyundai Motor and Toyota Motor Corporation. These findings clarify which electrolyte platforms are treated by individual firms as their core technologies and how these firms may position themselves for future commercialization.

4.1.4. Forward-citation characteristics by subtype

To complement the filing-count analysis, forward-citation statistics were examined for each electrolyte subtype (Table 7), as simple family

counts do not capture differences in technological influence. Because citation distributions are highly skewed, with a small number of families accounting for most citations, the mean, median, and share of families cited at least once are reported. Although sulfide electrolytes are the most numerous subtype (1965 families), their mean citation count (2.76) does not exceed that of oxide (3.24), polymer (3.23), or polymer–inorganic hybrid (4.69) families, indicating that filing volume does not directly translate into per-family technological influence. To account for differences in citation accrual time, an age-normalized metric (citations per year since filing) was also calculated. After normalization, halide families reach a per-year citation rate (0.38) comparable to sulfides (0.36), despite their smaller absolute count and more recent average filing year (2021). This suggests that emerging electrolyte platforms may be underrepresented when assessed solely by raw filing volume. The most frequently cited representative family in each subtype is listed in Table S1. Forward citations are used here as a proxy for technological influence but do not reflect validated cell performance or commercialization readiness.

4.1.5. Electrolyte subtype portfolios across jurisdictions

The patent portfolios of each major jurisdiction by electrolyte subtype are visualized using a bubble chart in Fig. 6. The figure highlights the relative filing share of sulfide, oxide, polymer, and hybrid electrolytes. Excluding CN, most major filing jurisdictions exhibit broadly similar patterns: sulfide electrolytes account for the largest share of patent families, followed by oxides, polymers, and polymer–inorganic hybrids. This convergence suggests that, within these jurisdictions, sulfide systems constitute the dominant material platform for ASSB electrolytes. In contrast, CN displays a more balanced distribution across oxide, polymer, and sulfide electrolytes, with hybrid electrolytes representing a visible share of patent families. Such a distribution is characteristic of an earlier stage of technological development, in which multiple competing material options are explored in parallel. The diversified Chinese portfolio suggests that ASSB electrolyte R&D remains in a comparative exploration phase rather than having converged on a single dominant platform.

4.1.6. Hypothesis testing: regional maturity (H4)

The jurisdictional portfolio analysis supports the regional maturity hypothesis (H4). JP and KR, home to the most active ASSB applicants and firms with announced commercialization timelines, exhibit converged portfolios heavily concentrated on sulfide electrolytes. This convergence suggests that applicants in these jurisdictions have largely completed the platform selection phase and have focused their R&D resources on the material family perceived as most viable for near-term commercialization. In contrast, CN displays a more balanced distribution of oxides, polymers, and sulfides, with hybrids representing a visible share of patent families. This diversified portfolio is characteristic of an earlier stage in technological maturity, in which multiple competing options remain under active exploration. The Chinese pattern may reflect either a deliberate strategy to maintain technological optionality or a less-consolidated consensus regarding optimal electrolyte platforms. Both interpretations support the prediction of H4 that portfolio concentration positively correlates with technological maturity.

This interpretation is further supported by a quantitative measure of portfolio concentration. For each jurisdiction, the Herfindahl–Hirschman Index (HHI) of electrolyte-subtype distribution was calculated, where higher values indicate greater concentration (Table S2). Japan and Korea show the most concentrated portfolios (HHI = 0.48 and 0.40), dominated by sulfide filings (62% and 57%), corresponding to effective subtype numbers of approximately 2.1 and 2.5, respectively. In contrast, China exhibits the most diversified portfolio (HHI = 0.24; sulfide share = 24%), corresponding to approximately 4.2 effective subtypes. This gradient is consistent with H4, which posits a positive association between portfolio concentration and technological maturity. However, portfolio concentration may also reflect differences in industrial structure, applicant composition, and national filing strategies rather than technological maturity alone. The EPO is excluded from this comparison due to a small sample size ($n = 13$).

4.2. Segmented trend analysis

Segmented trends in patent filings by electrolyte subtype are presented in Fig. 7 and Fig. 8, while the corresponding numerical data are

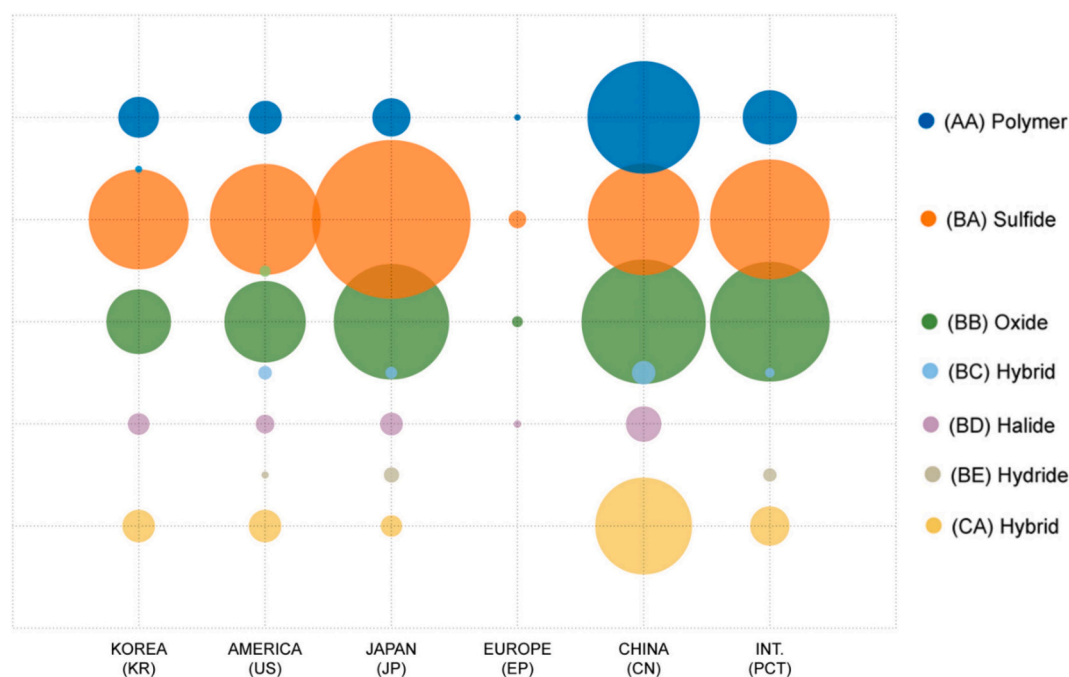


Fig. 6. Country-level distribution of patent families by electrolyte subtype for major ASSB-filing jurisdictions (bubble chart).

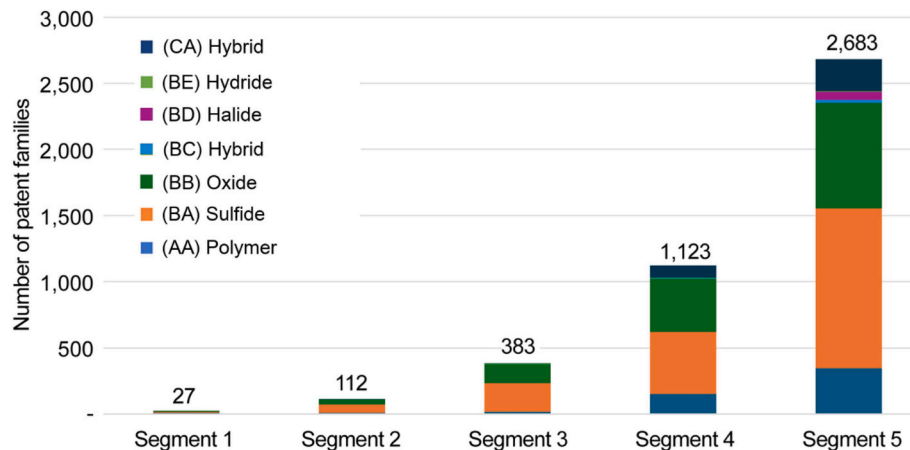


Fig. 7. Segmented trends in patent filings by electrolyte subtype: Absolute number of patent families in five 5-y segments.

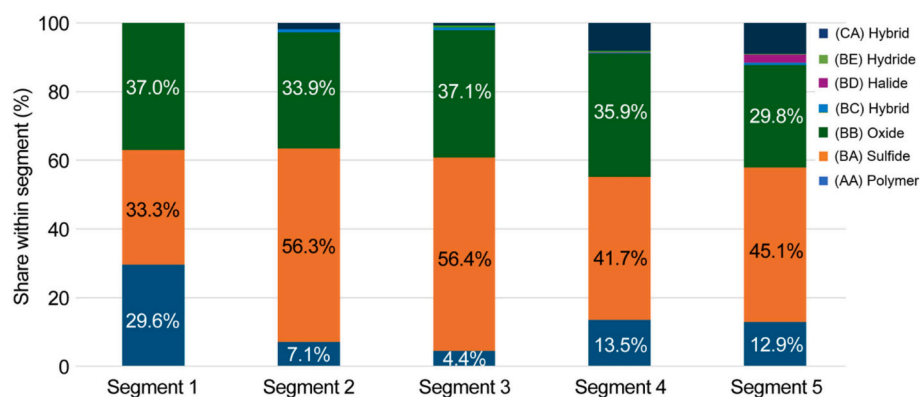


Fig. 8. Segmented trends in patent filings by electrolyte subtype: Relative filing share of each electrolyte subtype within total filings per 5-y segment.

provided in Tables 9 and 10, respectively. The absolute number of patent families in each 5-y segment is shown in Fig. 7, while Fig. 8 depicts the relative filing share of each electrolyte subtype within total filings per segment. The segments (1999–2003, 2004–2008, 2009–2013, 2014–2018, and 2019–2023) were defined in Section 3 to reduce short-term fluctuations and capture medium-term shifts in technology focus. In absolute terms (Fig. 7), filings for all electrolyte subtypes increased over time, confirming growing R&D interest across the entire material spectrum. The overall patent volume rose markedly in Segments 2 and 4. In Segment 2, the increase was driven primarily by sulfide electrolytes, whereas in Segment 4, the growth was driven mainly by oxide electrolytes. These temporal patterns align with developments in the broader battery industry. Segment 2 coincides with heightened awareness of explosion and fire risks in conventional liquid-electrolyte LIBs and with the emergence of high-conductivity sulfide electrolytes, including LGPS-type materials. Segment 4 followed the intensive academic development

Table 9

Segmented trends in patent filings by electrolyte subtype: Absolute number of patent families in five 5-y segments.

Subtype	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
Hybrid (CA)	–	2	3	91	242
Hydride (BE)	–	–	2	5	4
Halide (BD)	–	–	–	1	65
Hybrid (BC)	–	1	3	3	18
Oxide (BB)	10	38	142	403	800
Sulfide (BA)	9	63	216	468	1209
Polymer (AA)	8	8	17	152	345
Total	27	112	383	1123	2683

Table 10

Segmented trends in patent filings by electrolyte subtype: Relative filing share of each electrolyte subtype within total filings per 5-y segment.

Subtype	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
Hybrid (CA)	–	2%	1%	8%	9%
Hydride (BE)	–	–	1%	0%	0%
Halide (BD)	–	–	–	0%	2%
Hybrid (BC)	–	1%	1%	1%	1%
Oxide (BB)	37%	34%	37%	36%	30%
Sulfide (BA)	33%	56%	56%	42%	45%
Polymer (AA)	30%	7%	4%	13%	13%
Total	100%	100%	100%	100%	100%

* Values below 0.5% are rounded to 0% but indicate a non-zero relative share.

of garnet-type oxide conductors, initiated by the report of cubic $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ (LLZO) by Murugan et al. in 2007 [23], and coincided with major EV battery safety incidents in 2014–2015. Together, these developments were associated with renewed patenting activity in oxide electrolytes, driven by their perceived advantages as safer or complementary alternatives to sulfides.

The analysis of relative filing shares (Fig. 8) reveals more differentiated trends. Polymer electrolytes exhibit a declining relative share in later segments, whereas polymer–inorganic hybrids become prominent from Segment 4 onward and maintain a comparable share in Segment 5. This co-evolution is best interpreted as a convergence rather than a straightforward substitution: standalone polymer filings continue to grow (152 to 345 families between Segments 4 and 5) even as polymer–inorganic hybrids rise rapidly (91 to 242 families over the same

period), indicating that polymers are increasingly incorporated as a functional component of hybrid systems while still being pursued in their own right. In hybrid architectures, polymers contribute processability and mechanical compliance while inorganic phases supply ionic conductivity. This shift toward hybrid, more readily processable architectures is consistent with the processability-optimization phase of the proposed evolution pattern (H1), in which manufacturability and large-area compatibility become increasingly prominent R&D priorities. Sulfide electrolytes account for the largest relative filing share in Segment 2, confirming their position as the primary focus of ASSB electrolyte R&D during that period. Although the present analysis resolves electrolytes at the family level, the sulfide class itself encompasses considerable internal diversity—including thio-LISICON, $\text{Li}_2\text{S-P}_2\text{S}_5$ glasses and glass-ceramics, LGPS-type conductors, and argyrodite-type $\text{Li}_6\text{PS}_5\text{X}$ compositions. The scientific literature suggests a broad internal progression within this class, from earlier thio-LISICON and binary $\text{Li}_2\text{S-P}_2\text{S}_5$ systems toward higher-conductivity crystalline conductors such as LGPS-type and argyrodite-type compositions, including halogen-substituted variants that offer improved conductivity and processability. A material-resolved, segment-level analysis of these sulfide subtypes is beyond the scope of the present family-level classification but represents a valuable direction for future work. Oxide electrolytes show an increase in related absolute filing counts but gradually lose the relative filing share, indicating a transition from a primary focus to a complementary role within the overall patent portfolio distribution. Sulfide-oxide hybrid electrolytes appeared in Segment 2 but did not attain a substantial relative filing share. Halide electrolytes emerged in Segment 4 and increased markedly in Segment 5, reflecting their recent recognition as promising platforms. Hydride electrolytes appeared from Segment 3 onward but remained a niche subtype with only a small number of filings. Overall, the segmented trend analysis shows that sulfides have consolidated their position as the dominant material system, whereas halides and polymer-inorganic hybrids are emerging as fast-growing alternatives. Oxide electrolytes are increasingly assuming roles as complementary materials in addressing specific stability and processing challenges.

4.2.1. Hypothesis testing: technology evolution patterns (H1, H1-1, and H3)

The segmented trend data are consistent with the hypothesized technology evolution pattern (H1). In Segment 1 (1999–2003), the three main electrolyte families, polymer, sulfide, and oxide, held roughly comparable shares (30%, 33%, and 37%, respectively), indicating an early exploration phase without clear platform dominance. In Segment 2 (2004–2008), sulfide electrolytes surged to 56% of filings. This surge followed seminal reports of high-conductivity thio-LISICON sulfide conductors in the early 2000s (e.g., the $\text{Li}_2\text{S-GeS}_2\text{-P}_2\text{S}_5$ system reported by Kanno and Murayama in 2001 [24]), alongside growing awareness of safety limitations in liquid-electrolyte LIBs; the subsequent report of LGPS-type materials in 2011 [25] reinforced this focus into Segment 3. This development reflects the “conductivity-first” prioritization predicted by H1: Once sulfides demonstrated liquid-like ionic conductivity at room temperature, R&D attention rapidly consolidated around this platform.

The subsequent segments show evidence of the transition to “stability” and “processability” priorities. In Segment 3 (2009–2013), oxide electrolytes continued to increase in absolute filing counts, whereas sulfides remained dominant in relative share, suggesting parallel efforts to address interfacial and chemical stability challenges. In Segments 4–5 (2014–2023), the emergence of halide electrolytes (from 0% to 2%) and the rapid growth of polymer-inorganic hybrids (from 1% to 9%) indicate increasing attention to processability and environmental tolerance – attributes that are directly relevant to manufacturing scale-up. These patterns are consistent with the sequential prioritization hypothesis (H1).

The oxide repositioning hypothesis (H1-1) is also supported by the

segmented trend data. Despite the continuous growth in absolute filings (from 142 families in Segment 3 to 800 in Segment 5) for oxide electrolytes, their relative share declined from 37% to 30%. Concurrently, filings for sulfide-oxide hybrids (BC) increased from three to 18 families, while polymer-inorganic hybrids (CA) – which often incorporate oxide fillers – grew from 91 to 242 families. This pattern suggests that oxides are increasingly utilized for their stability and mechanical robustness in hybrid architectures rather than as standalone electrolyte platforms, thereby supporting the “functional complement” repositioning predicted by H1-1. To examine this repositioning more directly, oxide (BB) patents from Segments 3–5 were sub-coded based on the abstract and independent claim as either standalone/bulk electrolytes (S) or complementary applications such as protective layers, coatings, or composite components (C). Patents whose role could not be determined were classified as unclear (U) and excluded from the proportional analysis (see Section 3.4). Among the classified (S + C) patents, the share of complementary applications increased steadily from 6.8% in Segment 3 to 13.0% in Segment 4 and 19.6% in Segment 5. This monotonic increase is statistically significant (Cochran–Armitage trend test, $z = 3.9$, $p < 0.001$). The result provides direct evidence that, within the oxide class, patents increasingly position oxides in complementary rather than standalone roles, supporting the “functional complement” repositioning predicted by H1-1. However, standalone applications remain the dominant use in every segment, suggesting a gradual repositioning rather than a fundamental shift. The complementary platform emergence hypothesis (H3) is strongly supported by the Segment 5 data. Halide electrolytes, which were absent from the dataset through Segment 3 and accounted for only one family in Segment 4, increased to 65 families in Segment 5, showing a growth trajectory far exceeding that of the other subtypes in proportional terms. This rapid emergence followed the consolidation of sulfides as the dominant platform and directly addresses sulfide-specific limitations (including moisture sensitivity and H_2S evolution), while maintaining competitive ionic conductivity. Similarly, the polymer-inorganic hybrids grew from 91 to 242 families between Segments 4 and 5, reflecting efforts to integrate inorganic conductivity with polymer processability. These patterns confirm that complementary platforms emerge rapidly once the limitations of the dominant platform become widely recognized (H3).

The subtype composition changed significantly across the five segments ($\chi^2(24) = 141.7$, $p < 0.001$; Monte Carlo $p < 0.001$; Table S3). Trend tests supported the hypothesized directional shifts: the shares of halide ($z = +5.3$, $p < 0.001$) and polymer-inorganic hybrid electrolytes ($z = +5.5$, $p < 0.001$) increased significantly (H3), whereas the oxide share declined ($z = -3.6$, $p < 0.001$), consistent with its repositioning toward complementary applications (H1-1). Although sulfides remained the dominant subtype throughout, their share followed a non-monotonic trajectory, peaking in Segments 2–3 before partially receding as complementary platforms gained prominence, a pattern also consistent with H3. Together, these results confirm the predicted changes in patent composition, although they do not by themselves establish the causal ordering of R&D priorities.

4.3. R&D collaboration hub network analysis

The R&D collaboration network derived from 524 patent families jointly filed by two or more institutions is visualized in Fig. 9 and Fig. 10; the complete co-applicant network is provided in Fig. S1. The sub-network centered on the top 20 hubs ranked by CIs is highlighted in Fig. 9. Fig. 10 presents the local collaboration structures surrounding the top five hubs, emphasizing their intermediary roles between firms and research organizations. Table 11 lists the top 20 hubs and their CIs, while Tables 12–14 classify these hubs by organizational type (Table 12), national distribution (Table 13), and dominant electrolyte subtype (Table 14).

ASSB electrolyte technology integrates materials chemistry, interfacial engineering, manufacturing processes, and cell design, making it

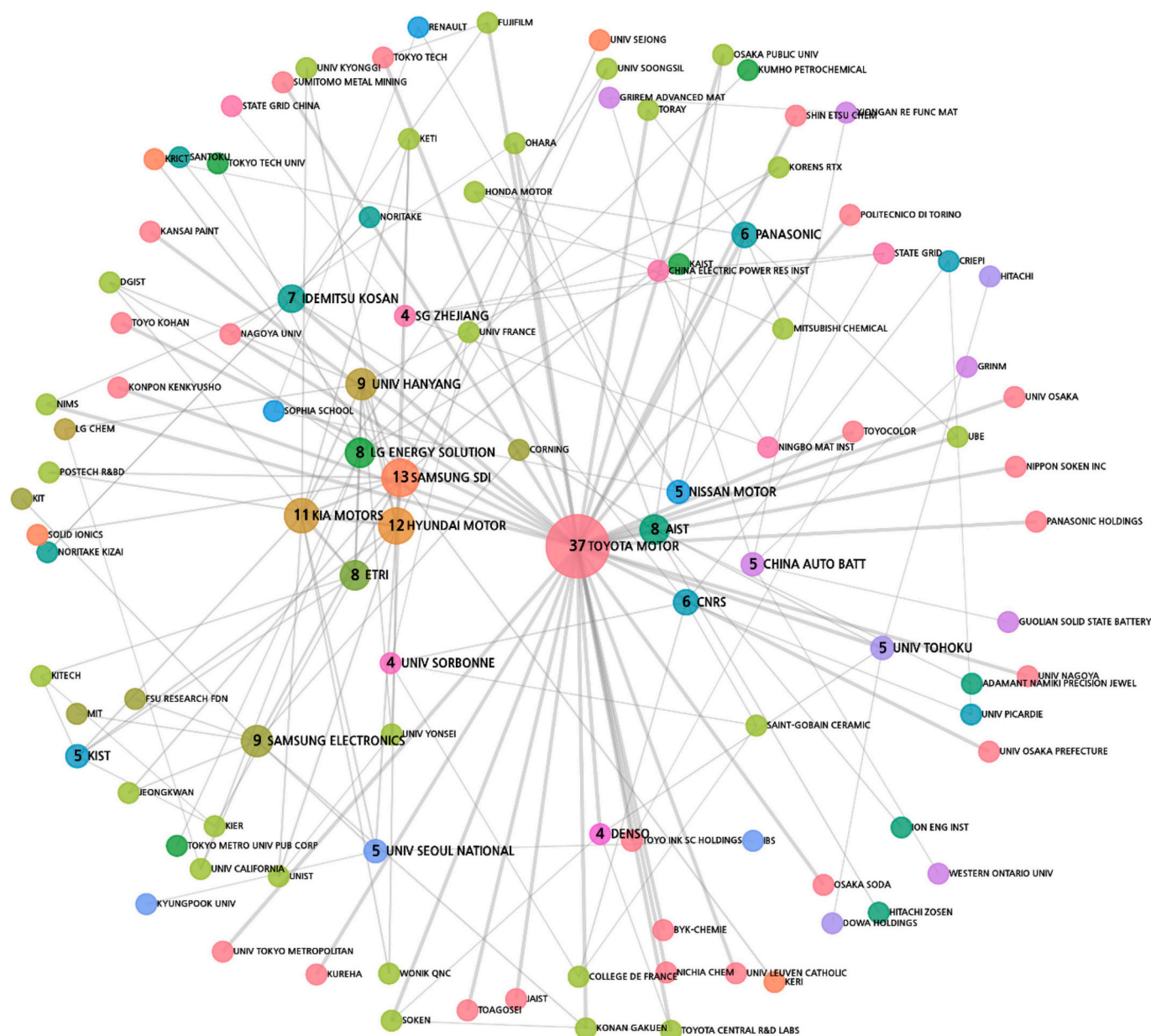


Fig. 9. R&D collaboration network of ASSB electrolyte patents: Collaboration sub-network centered on the top 20 hub institutions with the highest CIs.

difficult for a single institution to address all relevant technical challenges independently. The co-applicant analysis provides several insights into how R&D collaboration is organized in this complex field. First, the top 20 hubs comprise approximately equal numbers of firms and public research organizations (universities and public institutes) (Table 12). Among the top ten, Hanyang University (KR), ETRI (KR), and AIST (JP) function as technological intermediaries that connect multiple industrial partners. Their central positions in the network indicate strong capabilities in coordinating collaborative projects and integrating dispersed technical components into high-complexity solutions. Second, in terms of national distribution, KR and JP dominate the top 20 hubs, followed by CN and France (Table 13). This suggests that Korean applicants, in particular, are highly active in collaborative technology development for ASSB electrolytes and frequently engage in co-application activities with other firms and research institutions. Third, when the dominant electrolyte subtype of each hub was considered, 15 of the top 20 hubs focused primarily on sulfide electrolytes, four on oxide electrolytes, and one on halide electrolytes (Table 14). This

distribution reflects material-specific differences in the underlying technical complexity. Sulfide electrolytes pose multi-layered problems—including interfacial instability, moisture sensitivity (H_2S generation), structural fragility and solid–solid contact issues—that typically require the integration of expertise in materials chemistry, process engineering, interfacial science, and advanced characterization. Oxide-centered hubs constitute the second group, reflecting the need for specialized knowledge to address issues such as high-temperature sintering, poor interfacial contact with Li metal, and grain-boundary conductivity losses. In contrast, the relatively small number of halide-centered hubs suggests that, although halide electrolytes are technologically promising, large-scale multi-institutional collaboration remains at an early stage of development. Normalized centrality measures (Table S4) indicate that collaboration volume and network centrality do not always coincide. Although Toyota Motor has the highest CI, its combination of high betweenness and low eigenvector centrality suggests a brokerage role linking otherwise weakly connected partners, rather than integration within a densely connected core.

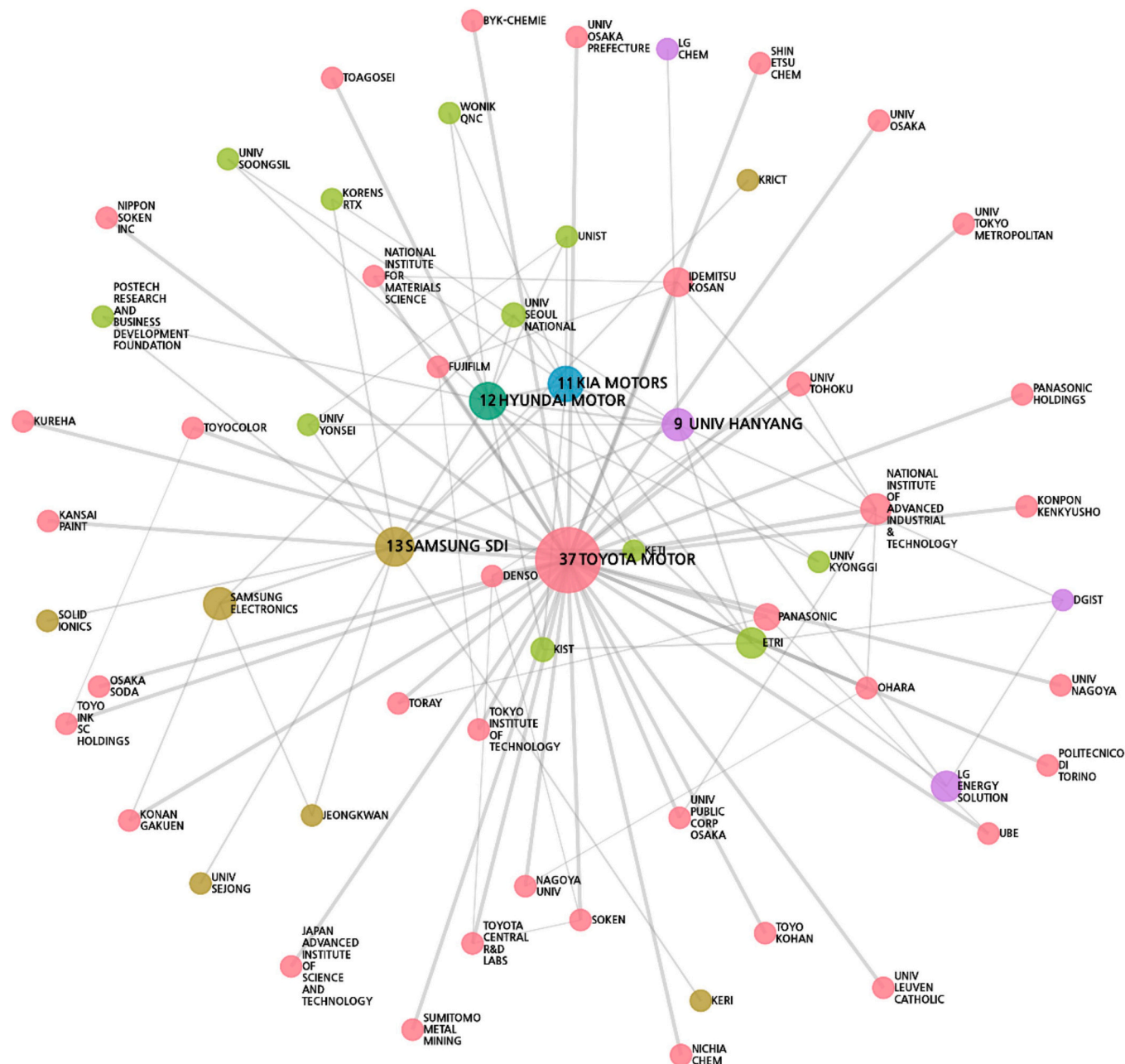


Fig. 10. R&D collaboration network of ASSB electrolyte patents: Local collaboration structures surrounding the top five hubs, highlighting their bridging roles between firms and research organizations.

4.3.1. Hypothesis testing: collaboration intensity and organizational composition (H2 and H2-1)

The collaboration network analysis provides strong support for the complexity–collaboration hypothesis (H2). Among the top 20 collaboration hubs, 15 (75%) primarily focused on sulfide electrolytes, the material family associated with the most multi-layered technical challenges (including moisture sensitivity, interfacial instability, mechanical brittleness, and H₂S generation). Four hubs (20%) focused on oxide electrolytes, which presented substantial but comparatively fewer concurrent challenges (such as high-temperature sintering and interfacial resistance). Only one hub (5%) focused on halide electrolytes, consistent with the more recent emergence of this material family and its still-developing technical knowledge base. This distribution directly mirrors the relative technical complexity of each electrolyte family, supporting the prediction of H2 that material-specific complexity is positively associated with collaboration intensity. To determine whether

hub formation reflects technical complexity rather than the larger filing volume of sulfide electrolytes, the share of each subtype among the top-20 hubs was compared with its share in the overall patent dataset (Fig. S2). If hub formation were driven solely by filing volume, these shares would be similar. Instead, sulfide electrolytes are substantially over-represented among hubs relative to their filing share (75% vs. 45%), whereas oxide electrolytes are under-represented (20% vs. 32%). This pattern suggests that the concentration of collaboration around sulfides cannot be explained by filing volume alone, providing additional support for H2. However, material-specific complexity is likely only one contributing factor; differences in technological maturity, commercialization proximity, and the challenges associated with other electrolyte families may also influence collaboration intensity. The organizational composition hypothesis (H2-1) was also confirmed. Prior research consistently reports that universities and public research institutes serve as the dominant technological intermediaries in emerging

Table 11

Top 20 R&D collaboration hubs in ASSB electrolyte patents and their CIs.

Rank	Organizational type	Abbreviation of applicants	Full name	Dominant subtype	Nationality	CI
1	Firm	TOYOTA MOTOR	Toyota Motor Corporation	Sulfide	JP	37
2	Firm	SAMSUNG SDI	Samsung SDI Co., Ltd.	Sulfide	KR	13
3	Firm	HYUNDAI MOTOR	Hyundai Motor Company	Sulfide	KR	12
4	Firm	KIA MOTORS	Kia Corporation	Sulfide	KR	11
5	Academia	UNIV HANYANG	Hanyang University	Sulfide	KR	9
6	Firm	SAMSUNG ELECTRONICS	Samsung Electronics Co., Ltd.	Sulfide	KR	9
7	Academia	ETRI	Electronics and Telecommunications Research Institute (ETRI)	Sulfide	KR	8
8	Firm	LG ENERGY SOLUTION	LG Energy Solution., Ltd.	Sulfide	KR	8
9	Academia	AIST	National Institute of Advanced Industrial Science & Technology	Oxide	JP	8
10	Firm	IDEMITSU KOSAN	Idemitsu Kosan Co., Ltd.	Sulfide	JP	7
11	Firm	PANASONIC	Panasonic Corporation	Sulfide	JP	6
12	Academia	CNRS	French National Centre for Scientific Research	Sulfide	FR	6
13	Academia	STATE GRID ZHEJIANG ELECTRIC POWER	State Grid Zhejiang Electric Power Co., Ltd.	Sulfide	CN	6
14	Academia	KIST	Korea Institute of Science and Technology	Sulfide	KR	5
15	Firm	NISSAN MOTOR	Nissan Motor Co., Ltd.	Sulfide	JP	5
16	Academia	UNIV SEOUL NATIONAL	Seoul National University	Oxide	KR	5
17	Academia	UNIV TOHOKU	Tohoku University	Oxide	JP	5
18	Academia	CHINA AUTOMOTIVE BATTERY RES INST	China Automotive Battery Research Institute Co., Ltd.	Halide	CN	5
19	Firm	DENSO	Denso Corporation	Oxide	JP	4
20	Academia	UNIV SORBONNE	Sorbonne University	Sulfide	FR	4

* CI, collaboration index, defined as the number of distinct co-applicant partner institutions, corresponding to the degree centrality of an institution in the co-applicant network. Normalized betweenness and eigenvector centrality for the same institutions are reported in Table S4.

Table 12

Share of firms versus academia in the top 20 collaboration hubs.

Organizational Type	Firm	Academia
Count (n)	10	10
Share (%)	50%	50%

Table 13

National distribution of the top 20 collaboration hubs.

Country Distribution	KR	JP	CN	FR
Count (n)	9	7	2	2
Share (%)	45%	35%	10%	10%

Table 14

Electrolyte subtype distribution among the top 20 collaboration hubs.

Electrolyte Subtype	Sulfide	Oxide	Halide
Count (n)	15	4	1
Share (%)	75%	20%	5%

technology fields [9,21,22]. However, among the top 20 ASSB electrolyte collaboration hubs identified in this study, firms and academic institutions were equally represented (50% each). This balanced distribution contrasts markedly with the academia-dominated patterns typically observed in emerging technologies and supports the prediction of H2-1 that ASSB electrolyte development requires the integration of dual competencies. This elevated representation of firms can be attributed to several ASSB-specific characteristics. First, the inseparability of materials and processes: The moisture sensitivity of sulfide electrolytes, cold-pressing optimization, and solid–solid contact formation can only be validated in actual manufacturing environments, which require firm-level process expertise. Second, the significance of scale-up know-how: The gap between laboratory-scale material synthesis and large-area cell fabrication is particularly pronounced for solid electrolytes, favoring firms with pilot-line capabilities. Third, vertical integration strategies: Major automakers and battery manufacturers (including Toyota Motor

Corporation, Samsung SDI Co., Ltd., and Hyundai Motor Company) are pursuing in-house technology development spanning fundamental materials research to cell design. This strategy is driven by technical integration requirements and intellectual property protection considerations. Fourth, proximity to commercialization: As ASSB technology approaches market readiness, firms have stronger incentives to participate directly in collaborative patenting rather than relying solely on licensed academic inventions.

Finally, distinct collaboration strategies were observed among the key technological intermediaries. Toyota Motor Corporation exhibits a domestically oriented, relatively closed collaboration structure. Among its 37 co-applicant partners, almost all are Japanese entities (e.g., Panasonic Corporation, SOKEN (or Toyota Central R&D Labs), NIMS (National Institute for Materials Science), Kureha Corporation, AIST, Denso Corporation, and Idemitsu Kosan Co., Ltd.). Only a limited number of overseas partners are involved, such as BYK-Chemie (Germany), Politecnico di Torino (Italy) and KU Leuven (Belgium). This pattern indicates a strategy aimed at internalizing core ASSB technologies within the domestic innovation ecosystem and minimizing potential knowledge spillovers. Samsung SDI Co., Ltd., Hyundai Motor Company, and Kia Corporation also rely predominantly on domestic partners; however, their collaborations are strongly oriented toward universities and public research institutes. For these firms, more than 90% of co-applications involve Korean institutions, and over 75% of the partners are public research organizations. This pattern indicates a collaboration model in which academic and public-sector collaborations are leveraged to build foundational materials and interfacial technologies, while downstream product development is retained in-house. Several factors may contribute to this domestically oriented collaboration pattern. Geographic and linguistic proximity can reduce coordination costs and facilitate knowledge exchange, while national R&D funding programs often incentivize industry–academia consortia within national boundaries. In addition, firms may prefer to retain core ASSB knowledge within the domestic innovation ecosystem to strengthen intellectual-property protection and enhance supply-chain security. In contrast, Samsung Electronics Co., Ltd. has adopted a globally open collaboration strategy, engaging in co-applications with Corning Incorporated (US), Karlsruhe Institute of Technology (Germany), Konan Gakuen (JP),

Massachusetts Institute of Technology (US), Florida State University (US), and the University of California (US). This approach reflects the active utilization of international knowledge networks in frontier domains, such as novel electrolyte compositions, advanced characterization, and interfacial engineering.

Taken together, these findings reveal systematic differences in collaboration models: Toyota Motor Corporation follows a domestically oriented and relatively closed ecosystem approach. Samsung SDI Co., Ltd., Hyundai Motor Company, and Kia Corporation favor domestic collaboration centered on universities and public research institutes for foundational technologies. In contrast, Samsung Electronics Co., Ltd. pursues a globally open and exploratory collaboration strategy. These contrasting models reflect different approaches to managing the technical risks associated with ASSB electrolyte development, protecting intellectual property, and securing supply chains. They are therefore likely to result in differentiated commercialization pathways.

4.4. Implications for technology commercialization and industry roadmaps

The patent trends and collaboration patterns identified in this study may provide a useful basis for discussing technology commercialization strategies and industry roadmap development in the ASSB field. Patent filings and citations reflect strategic R&D allocation and technological influence; they do not directly measure cell-level performance, manufacturing readiness, or commercialization timelines. The commercialization-related observations below are therefore best understood as indirect, patent-based signals rather than as assessments of demonstrated device performance.

The dominance of sulfide electrolytes in both patent filings (45% of total) and collaboration networks (75% of top hubs) may indicate that sulfide-based architectures are currently viewed as among the most commercially advanced pathways for near-term ASSB development. This prominence, however, reflects accumulated and current R&D concentration to date rather than direct evidence of the future technological trajectory. The concentration of sulfide-related patenting among firms that have publicly discussed commercialization timelines is consistent with ongoing efforts to translate pilot-scale development into larger-scale manufacturing. The rapid increase in halide-related patent families in the most recent segment suggests growing strategic interest in this platform, although its position on the commercialization timeline remains less certain than that of sulfide-based systems.

The coexistence of multiple electrolyte platforms in active R&D portfolios suggests a possible market segmentation rather than winner-take-all dynamics. The observed patenting patterns are consistent with a scenario in which sulfide-based systems are prioritized for high-energy automotive applications, polymer-based or hybrid systems for flexible form factors, and oxide-based systems for applications where thermal robustness and long service life are emphasized [26,27]. However, such positioning remains subject to further technological and market developments.

A challenge common to all ASSB electrolyte platforms is the stability of the electrode–electrolyte interface, a key determinant of cycle life, rate capability, and commercial viability [28,29]. Because the present classification is organized by electrolyte material rather than cell function, interface-related inventions are incorporated into the corresponding material subtypes (e.g., coatings and buffer layers for sulfide electrolytes are classified within the sulfide category). Nevertheless, the prominence of interfacial challenges across major electrolyte families – reflected in the technical characteristics summarized in Table 1 and the collaboration patterns discussed in Section 4.3.1 – suggests that interface engineering is a major cross-cutting focus of ASSB electrolyte R&D. Future research could examine interface-related patents across electrolyte families from a functional perspective, including coatings, interlayers, and interphase-stabilization strategies.

The stronger convergence of Japanese and Korean portfolios around

sulfide electrolytes may reflect a more focused development strategy centered on scale-up and supply-chain alignment. In contrast, the more diversified Chinese portfolio may reflect broader exploration, portfolio diversification, or strategic optionality. These regional differences are consistent with broader shifts in battery manufacturing IP, where China has emerged as the dominant patent filer in cell production technologies in recent years [11]. For firms and research institutions considering market entry, these regional patterns may serve as reference points for competitive positioning and partnership development.

The balanced firm–academia distribution among collaboration hubs (50%–50%) and the material-specific clustering of partnerships suggest that effective ASSB development may benefit from integrated ecosystems spanning fundamental research and manufacturing process expertise. The distinct collaboration strategies observed—such as Toyota's domestically oriented approach versus Samsung Electronics' globally distributed partnerships—illustrate different approaches to managing technology development pipelines. These observations may offer a useful analytical basis for discussing consortium formation, licensing approaches, and vertical integration strategies in ASSB commercialization.

5. Outlook

From a technology development perspective, these findings highlight critical junctures in ASSB electrolyte innovation where current R&D portfolio choices may shape near-term commercialization pathways. The dominance of sulfide electrolytes in patenting activity and collaboration networks may indicate that this platform is currently viewed as one of the most commercially advanced pathways for early ASSB deployment, with the associated requirements for controlled-atmosphere manufacturing and specialized processing infrastructure. The growing visibility of halides and polymer–inorganic hybrids may point to alternative development pathways with different processing requirements and scalability profiles. These platforms appear to be at comparatively earlier stages of development, but they may prove relevant in application segments where moisture sensitivity, interfacial compatibility, or processing constraints limit the practicality of sulfide-based systems. For industry stakeholders and R&D planners, shifts in patent portfolio composition and collaboration structures may provide useful, though indirect, signals of technology maturation and emerging competitive dynamics.

This study has several limitations that warrant consideration. The present analysis is based on IP5 and PCT patent data and therefore does not capture non-patented know-how, early-stage academic activity, or filings outside those jurisdictions. The 18-month publication lag means that the segmented trends reflect past strategic decisions more directly than ongoing, non-public R&D activities. Although expert-driven classification was applied consistently, borderline cases necessarily involve judgment. Future work could combine automated text-mining approaches with expert classification to improve scalability and reproducibility. It could also expand the analytical framework by incorporating additional jurisdictions, start-up ecosystems, patent citation networks, experimental performance datasets, and techno-economic assessments, thereby providing a more comprehensive view of ASSB electrolyte trajectories. The exclusion of non-lithium chemistries (noise category N3) defines the scope of this study but also highlights a natural avenue for extension. As discussed in the previous paper [30], all-solid-state sodium batteries are following a trajectory similar to that of lithium systems, including a recent shift toward halide electrolytes and the continued importance of interface-engineering strategies to address solid–solid interfacial resistance and electrode–electrolyte instability. These parallels suggest that the conductivity–stability–processability trade-offs and platform dynamics identified here may also characterize sodium, and potentially potassium, systems. However, the larger ionic radius of sodium introduces distinct transport and mechanical constraints that may alter the relative

importance of individual electrolyte platforms, including the extent of sulfide dominance. Applying the material-resolved patent framework developed in this study to sodium and potassium solid electrolytes therefore represents a promising direction for future research.

6. Conclusion

This study used a material-resolved patent analysis of 4328 patent families to examine the evolution of ASSB electrolyte technologies and their R&D collaboration structures. The results were consistent with six hypotheses concerning technological prioritization, platform transition, collaboration intensity, organizational composition, complementary platform emergence, and jurisdictional maturity. Overall, the findings are consistent with a sequential development pattern in which R&D attention appears to shift from conductivity to stability and then to processability. These patterns describe shifts in the composition of patent filings and should be read as suggestive of, rather than direct evidence for, an underlying causal ordering of R&D priorities. Within this pattern, sulfides have to date been the most prominent platform, whereas oxides increasingly shifted toward hybrid and complementary roles. This prominence reflects accumulated and current R&D concentration rather than a definitive indication of the future direction of ASSB electrolyte technology. The rapid rise of halides and polymer–inorganic hybrids suggests that the field may be diversifying, rather than converging on a single platform, toward materials that address limitations associated with sulfide-based systems. In addition, the observed collaboration patterns indicate that material-specific technical complexity is associated with greater collaboration intensity and that leading collaboration hubs show a relatively balanced firm–academia composition. This suggests that ASSB electrolyte innovation may rely on a more organizationally balanced network structure than is often reported in other emerging technology domains. From a methodological perspective, this study contributes a field-specific noise taxonomy and a material-based classification scheme that can be reused in future ASSB patent analyses. More broadly, it shows how material-specific characteristics shape both technological trajectories and collaboration structures in a commercialization-oriented domain. The combined use of segmented trend analysis and collaboration-hub metrics may also provide a useful analytical basis for R&D roadmap design, partner selection, and public funding decisions.

Abbreviations

General/methods

ASSB	All-solid-state battery
CNIPA	China National Intellectual Property Administration
EPO	European Patent Office
ESG	Environmental, social, and governance
EV	Electric vehicle
IP5	Five largest intellectual property offices (EPO, JPO, KIPO, USPTO, CNIPA)
JPO	Japan Patent Office
KIPO	Korean Intellectual Property Office
LIB	Lithium-ion battery
PCT	Patent Cooperation Treaty
USPTO	United States Patent and Trademark Office
WIPO	World Intellectual Property Organization

Electrolyte materials & structures

LAGP	Lithium aluminum germanium phosphate
LATP	Lithium aluminum titanium phosphate
LGPS	Lithium germanium phosphorus sulfide
LLTO	Lithium lanthanum titanium oxide
LLZO	Lithium lanthanum zirconium oxide

NASICON	Sodium superionic conductor
PAN	Polyacrylonitrile
PEO	Poly(ethylene oxide)
PMMA	Poly(methyl methacrylate)
PVDF-HFP	Poly(vinylidene fluoride-co-hexafluoropropylene)

CRedit authorship contribution statement

Kyeong-Weon Park: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Young-Jun Lee:** Writing – original draft, Validation. **Ji-Wan Kim:** Validation, Formal analysis. **Da-ae Lim:** Validation, Formal analysis. **Ki Tae Kim:** Writing – review & editing, Supervision, Software, Resources. **Dong-Won Kim:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Claude Opus 4.7 (Anthropic) to improve readability and language editing. In addition, Gemini 3.1 Pro (Google) was used to assist with the preliminary functional sub-coding of oxide patents (standalone versus complementary use) described in Section 4.2.1; all such AI-assisted classifications were spot-checked by the first author, a registered patent attorney. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.est.2026.123916>.

Data availability

Data will be made available on request.

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