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Nanocomposite Designs for Enhanced Ion Conductivity in Solid-State Battery Electrolytes

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ABSTRACT

This study aims to analyze nanocomposite designs used to enhance ionic conductivity in solid-state battery electrolytes, with a focus on the relationship between material structure, interfacial behavior, and ion transport mechanisms. The study uses a qualitative case study approach based on a systematic literature review. Data were collected through documentation of academic articles published between 2020 and 2025 from major scientific databases, including ScienceDirect, ACS Publications, Wiley Online Library, SpringerLink, MDPI, RSC Publishing, IOPscience, and Google Scholar. The selected documents were analyzed using thematic analysis. The findings reveal four main themes: polymer-ceramic synergy, filler morphology and dispersion, interface-controlled ion transport, and the balance between ionic conductivity, mechanical stability, electrochemical performance, and scalability. The results show that improved ionic conductivity does not depend only on filler addition, but on the alignment between nanofiller type, matrix compatibility, interfacial chemistry, and fabrication method. This study contributes to a deeper understanding of solid-state electrolyte design by positioning ionic conductivity as a structural and interfacial phenomenon. The findings imply that future battery electrolyte development should integrate conductivity, safety, stability, durability, and material feasibility. Further research should investigate polymer-ceramic interfaces through advanced characterization and explore sustainable nanofiller sources for scalable solid-state battery applications.

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1. Introduction

The development of solid-state batteries has become a central issue in modern energy storage research. The growing demand for electric vehicles, high-power electronic devices, and renewable energy storage systems requires batteries that are safer, more stable, and able to deliver higher energy density. Conventional lithium-ion batteries still face safety risks due to the use of flammable liquid electrolytes and unstable electrode-electrolyte interfaces. Song et al. (2023) argue that solid polymer electrolytes offer strong potential for lithium metal batteries, but their low ionic conductivity at room temperature remains a major limitation. Therefore, the development of solid-state battery electrolytes has become a critical research agenda for improving the safety and performance of next-generation batteries.

At the global level, solid-state batteries are viewed as a promising technology to reduce dependence on liquid electrolytes. Solid electrolytes function as ion transport media and physical separators between the cathode and anode. However, single-phase solid electrolytes often cannot meet all performance requirements. Ceramic electrolytes offer good ionic conductivity and mechanical strength, but they are brittle and often form poor interfacial contact with electrodes. Polymer electrolytes are more flexible and easier to process, but they generally show lower ionic conductivity. Yang and Wu (2022) explain that improving ion transport in solid electrolytes requires structural regulation, defect engineering, interface modification, and appropriate composite design.

Nanocomposite solid electrolytes have emerged as a promising solution because they combine the advantages of polymer and ceramic electrolytes. In this design, inorganic nanofillers such as SiO_2, TiO_2, LLZO, LLTO, LLZTO, LATP, and LAGTP are incorporated into polymer matrices such as PEO, PVDF, PVDF-HFP, or PEGDA. Tan et al. (2020) show that the in situ synthesis of SiO_2 nanoparticles in a PEO matrix can strengthen interactions among the polymer, lithium salt, and filler. Sivaraj et al. (2020) also found that adding LLTO nanofillers to a PVDF/$LiClO_4$ system can improve ionic conductivity by modifying the structure and enhancing ion migration pathways. These findings indicate that electrolyte performance depends not only on material selection, but also on filler dispersion and polymer-filler interaction.

The main challenge in nanocomposite design lies in the relationship between microstructure, ion transport pathways, and interfacial stability. Poorly dispersed fillers can form agglomerates and increase ion transport resistance. In contrast, fillers with suitable dimension, morphology, and concentration can reduce polymer crystallinity, expand the amorphous phase, and form percolated ion transport pathways. Wu et al. (2020) demonstrated that a 3D coral-like LLZO/PVDF structure can improve ionic conductivity and mechanical flexibility. Yu et al. (2021) further showed that a PEGDA-LLZTO composite design can produce an electrochemically stable electrolyte suitable for solid-state batteries. These studies suggest that nanocomposite electrolyte design should be understood as a structural system, not merely as a mixture of materials.

Recent studies still show several research gaps. Many studies report improved ionic conductivity values, but not all explain the mechanisms behind such improvement in depth. Zheng et al. (2023) emphasize that filler dimensional design, from 0D, 1D, 2D, to 3D frameworks, determines the effectiveness of ion transport pathways in composite solid electrolytes. Sand et al. (2024) also note that debate remains regarding whether dominant Li-ion conduction occurs in the polymer phase, ceramic phase, or at the polymer-ceramic interface. Meanwhile, Murali et al. (2024) highlight that scalability, cost, material compatibility, and long-term stability remain key barriers in developing nanocomposite electrolytes for solid-state batteries.

Based on these gaps, this study aims to analyze nanocomposite designs used to enhance ionic conductivity in solid-state battery electrolytes. The study focuses on nanofiller types, polymer matrices, fabrication methods, ion transport mechanisms, interfacial stability, and the implications of these designs for battery performance. Theoretically, this study contributes to a clearer understanding of the relationship between material structure and ion conduction mechanisms in composite electrolytes. Practically, it provides a conceptual basis for developing solid-state electrolytes that are safer, more conductive, more flexible, and more feasible for next-generation battery applications.

2. Materials and Methods

This study uses a qualitative approach with a case study design based on a systematic literature review. This approach was selected because the study does not aim to test statistical relationships. Instead, it seeks to understand in depth the design patterns of nanocomposites used to enhance ionic conductivity in solid-state battery electrolytes. The case study design allows detailed examination of material designs, including ceramic nanofillers, polymer matrices, 3D composite structures, and interfacial interactions. This design fits the research focus because the study examines processes, mechanisms, and scientific meanings found in academic literature. Braun and Clarke (2021) explain that qualitative research can identify conceptual patterns through systematic thematic analysis.

The study was conducted through desk research from January to March 2026. The research location was online because all data were collected from scientific articles available through academic databases. The databases used included ScienceDirect, ACS Publications, Wiley Online Library, SpringerLink, MDPI, RSC Publishing, IOPscience, and Google Scholar. The keywords included “nanocomposite solid electrolyte”, “composite polymer electrolyte”, “solid-state battery electrolyte”, “ionic conductivity”, “ceramic filler”, “polymer matrix”, “LLZO”, “LLTO”, “LATP”, “PVDF-HFP”, and “PEO-based electrolyte”. The search process followed PRISMA 2020 principles so that article identification, screening, eligibility assessment, and selection could be reported transparently. Page et al. (2021) state that systematic reporting strengthens the traceability of review procedures.

The subjects of this study were scientific documents, not human participants. The unit of analysis consisted of journal articles published between 2020 and 2025 that examined nanocomposite designs for solid-state battery electrolytes. The sources were selected using purposive sampling because the articles were chosen based on their direct relevance to the research objective. Campbell et al. (2020) explain that purposive sampling is appropriate when researchers need the most informative sources to answer a specific research focus. The inclusion criteria covered articles with active DOIs, articles discussing solid-state electrolytes or composite polymer electrolytes, articles explaining filler and matrix types, and articles presenting information on ionic conductivity. Articles were excluded if they had no DOI, were unrelated to electrolytes, focused only on electrodes, or lacked sufficient methodological information.

Data were collected through systematic documentation of selected articles. Each article was reviewed by reading the title, abstract, method, results, discussion, and conclusion. Extracted data included author names, year of publication, electrolyte type, material composition, nanofiller type, fabrication method, ionic conductivity value, measurement temperature, electrochemical stability, mechanical stability, cycling performance, and research limitations. Studies by Tan et al. (2020), Wu et al. (2020), Yu et al. (2021), Paste et al. (2024), and Olmedo-Martínez et al. (2024) were used to map variations in nanocomposite design. The extracted data were then organized in a data extraction table to support structured comparison across articles.

Data validation was carried out through source triangulation, documentation method triangulation, peer checking, and audit trail. Source triangulation was conducted by comparing articles from different journals, publishers, and material design approaches. Documentation method triangulation was conducted by checking consistency across the abstract, method, results, and discussion sections of each article. Peer checking was carried out by asking researchers or academics with expertise in battery materials, materials chemistry, or electrolyte technology to review the coding and theme formation process. An audit trail was maintained by storing search keywords, databases used, inclusion and exclusion reasons, data extraction tables, and the theme development process. Rethlefsen et al. (2021) emphasize that clear reporting of literature search strategies improves transparency and supports review replication.

Data were analyzed using thematic analysis. The first stage involved data familiarization through repeated reading of the selected articles. The second stage involved initial coding using codes such as “polymer matrix”, “ceramic filler”, “reduced crystallinity”, “interfacial pathway”, “3D framework”, “dendrite suppression”, “room-temperature conductivity”, and “electrochemical stability”. The third stage involved grouping codes into categories, including filler design strategy, ion transport mechanism, interfacial stability, and development challenges.

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The fourth stage involved constructing the main themes, namely nanocomposite design patterns, mechanisms of ionic conductivity enhancement, interfacial structure contribution, and future directions for solid-state electrolyte development. Lamba et al. (2022) show that thematic analysis can generate strong themes when coding, interpretation, and validation are conducted systematically.

3. Results and Discussions

The qualitative analysis of the selected articles produced four main themes. These themes describe how nanocomposite designs enhance ionic conductivity in solid-state battery electrolytes. The themes include: polymer-ceramic synergy, filler morphology and dispersion, interface-controlled ion transport, and the trade-off between conductivity, stability, and scalability. These themes show that ionic conductivity does not depend on a single material factor. It emerges from the interaction between matrix structure, filler characteristics, interfacial chemistry, and fabrication strategy.

The first theme is polymer-ceramic synergy as the foundation of nanocomposite electrolyte design. The reviewed studies show that polymer matrices provide flexibility, processability, and better electrode contact, while ceramic fillers contribute mechanical strength, thermal stability, and faster Li^+ migration pathways. This pattern appears in PEO, PVDF, PVDF-HFP, and PEGDA-based systems. In the analyzed documents, polymer-only electrolytes were often described as limited by low room-temperature conductivity. Ceramic-only electrolytes were often described as limited by brittleness and poor interfacial contact. Composite design therefore appears as a strategic response to the weaknesses of both systems. This finding supports the view that nanocomposite electrolytes work best when polymer and ceramic phases are designed as complementary components rather than independent additives.

The second theme is filler morphology and dispersion as determinants of ion transport pathways. The articles show that nanofillers improve ionic conductivity when they are well dispersed and able to form continuous or semi-continuous transport channels. Tan et al. (2020) showed that in situ SiO_2 formation in PEO strengthened interaction among filler, polymer, and lithium salt. Wu et al. (2020) showed that 3D coral-like LLZO/PVDF improved ionic conductivity and mechanical flexibility. Zheng et al. (2023) further emphasized that filler dimension, including 0D nanoparticles, 1D nanowires, 2D nanosheets, and 3D frameworks, strongly affects ion path optimization. These findings suggest that morphology controls not only the physical structure of the electrolyte, but also the spatial continuity of Li^+ migration.

The third theme is interface-controlled conductivity. The reviewed documents indicate that the polymer-ceramic interface plays a central role in improving or limiting ion movement. Several studies suggest that the interface can reduce polymer crystallinity, increase amorphous regions, and create more active sites for Li^+ transport. Sand et al. (2024) argued that the interface in ceramic-polymer electrolytes remains a debated zone because Li^+ conduction may occur through the polymer phase, ceramic phase, or interfacial region. This theme shows that the interface should not be treated as a passive boundary. It acts as an active transport region that can either facilitate or block ion migration depending on surface chemistry, filler loading, and matrix compatibility.

The fourth theme is the balance between conductivity, mechanical stability, and battery performance. High ionic conductivity alone does not guarantee strong battery performance. The reviewed articles show that composite electrolytes must also suppress dendrite growth, maintain electrochemical stability, and support long-term cycling. Yu et al. (2021) reported that PEGDA-LLZTO composite electrolytes offered good ionic conductivity and electrochemical stability. Paste et al. (2024) showed that A-LLTO nanoparticles in a self-healing polymer matrix supported room-temperature lithium metal battery operation. These findings indicate that successful nanocomposite design requires simultaneous optimization of ion transport, mechanical resistance, interfacial stability, and electrochemical compatibility.

A further finding concerns sustainability and material practicality. Most studies focus on conductivity enhancement, but some recent works begin to consider greener and more practical material sources. Sreejith et al. (2023) used waste seashell-based nanofiller in a cross-linked polymer composite electrolyte. This approach shows that nanocomposite electrolyte design can also connect with environmental concerns, resource efficiency, and cost reduction. In the broader context of electric vehicle development and renewable energy storage, this theme is important because future battery materials must be safe, high-performing, and scalable.

Overall, the findings show that enhanced ionic conductivity in solid-state battery electrolytes results from integrated nanocomposite design. The strongest pattern across the analyzed literature is that material performance improves when filler type, filler morphology, matrix compatibility, interfacial chemistry, and fabrication method are aligned. The data also show that the most promising designs are not merely those with the highest conductivity values. They are the designs that combine conductivity, stability, flexibility, safety, and practical manufacturability.

Discussion

The findings confirm that nanocomposite design is a strategic pathway for overcoming the main limitations of solid-state battery electrolytes. This result is consistent with Yang and Wu (2022), who explain that ion transport in solid electrolytes depends on structure, defects, interfaces, and material architecture. The present study strengthens this argument by showing that nanocomposite electrolytes function through multi-factor interaction. Conductivity enhancement does not emerge only from adding ceramic filler. It emerges when filler structure, polymer dynamics, and interfacial chemistry support each other.

The theme of polymer-ceramic synergy aligns with Qian et al. (2021), who argue that ceramic/polymer composite electrolytes combine the flexibility of polymers with the ionic and mechanical advantages of ceramic phases. This finding also supports Su et al. (2023), who explain that PEO/ceramic composite electrolytes require rational design to solve low room-temperature conductivity and weak interfacial compatibility. However, this study adds a qualitative perspective by showing that synergy is not automatic. Poor filler dispersion, weak compatibility, or excessive filler loading can weaken the expected benefits of composite design.

The finding on filler morphology supports Zheng et al. (2023), who show that filler dimensional design plays a key role in ion path optimization. The present analysis shows that 3D frameworks and structured fillers tend to offer better pathways than randomly dispersed particles because they create more continuous ion migration routes. Wu et al. (2020) demonstrated this through coral-like LLZO/PVDF composites. This suggests that future studies should move beyond simple filler addition and focus more on spatial design, filler orientation, and controlled architecture.

The discussion on interface-controlled conductivity is important because it offers a more critical view of nanocomposite electrolyte performance. Sand et al. (2024) noted that the role of the polymer-ceramic interface remains unresolved in many studies. Some results suggest that the interface improves Li^+ movement by reducing crystallinity and increasing free volume. Other results indicate that poor surface compatibility may create interfacial resistance. This study therefore interprets the interface as a decisive zone. It can act as a transport bridge or a transport barrier. This depends on how the filler surface interacts with polymer chains and lithium salts.

The findings also extend the discussion on battery safety. Solid-state electrolytes are often promoted as safer alternatives to liquid electrolytes. However, the reviewed literature shows that safety depends on more than electrolyte phase. It also depends on dendrite suppression, mechanical integrity, electrochemical window, and stable electrode contact. Yu et al. (2021) and Paste et al. (2024) show that well-designed composite electrolytes can improve stability in lithium

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metal battery systems. This means that nanocomposite design contributes not only to conductivity, but also to safety and cycling durability.

The sustainability theme offers another contribution. Most technical studies focus on electrochemical metrics, but future battery development also requires attention to material availability, environmental impact, and production feasibility. Sreejith et al. (2023) show that waste-derived nanofillers can support electrolyte development. This finding opens a new direction for research on green nanocomposite electrolytes. For countries involved in battery supply chains, including Indonesia, this point is relevant because battery innovation should not focus only on performance. It should also consider cost, local resources, environmental safety, and scalable processing.

Theoretically, this study contributes to the understanding of solid-state electrolyte design by framing ionic conductivity as a product of structural interaction. The findings support the idea that ion transport is shaped by polymer mobility, ceramic filler function, interfacial structure, and fabrication strategy. Practically, this study suggests that researchers should evaluate nanocomposite electrolytes through integrated indicators, including ionic conductivity, transference number, electrochemical stability, mechanical strength, dendrite resistance, and long-term cycling performance. A high conductivity value should not be treated as the only indicator of success.

Future research should examine polymer-ceramic interfaces more directly through advanced characterization and in situ analysis. Further studies should also compare 0D, 1D, 2D, and 3D filler structures under similar experimental conditions. This would help clarify which filler architecture provides the most stable ion transport pathway. In addition, future studies should explore low-cost and environmentally friendly fillers, scalable fabrication methods, and compatibility with high-voltage cathodes and lithium metal anodes. These directions can strengthen the transition from laboratory-scale electrolyte design to practical solid-state battery applications.

4. Conclusions

This study concludes that enhanced ionic conductivity in solid-state battery electrolytes depends on integrated nanocomposite design rather than the simple addition of fillers. The findings show that polymer-ceramic synergy, filler morphology, filler dispersion, interfacial chemistry, and fabrication strategy jointly shape Li^+ transport pathways. Nanofillers such as SiO_2, TiO_2, LLZO, LLTO, LLZTO, LATP, and LAGTP can reduce polymer crystallinity, expand amorphous regions, strengthen mechanical stability, and improve electrode-electrolyte compatibility when they are designed with appropriate structure and concentration. This study contributes to the literature by framing ionic conductivity as a structural and interfacial phenomenon, not only as an electrochemical value.

Theoretically, this study strengthens the understanding of ion transport mechanisms in composite solid electrolytes by highlighting the active role of the polymer-ceramic interface. Practically, the findings suggest that future electrolyte design should evaluate conductivity together with transference number, electrochemical stability, dendrite resistance, mechanical strength, cycling durability, and scalability. From a policy perspective, this study supports the need for research investment in safer and more sustainable battery materials, especially for countries developing electric vehicle and energy storage ecosystems. Future studies should examine polymer-ceramic interfaces through in situ characterization, compare filler dimensions under similar experimental conditions, and explore low-cost, environmentally friendly nanofillers for scalable solid-state battery production.

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