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Next-Generation Battery Breakthroughs: A Comprehensive Analysis of Liquid, Gel, and Solid Electrolyte Advancements in Performance, Safety, and Energy Storage Potential

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Abstract

Electrolytes are central to the evolution of battery technologies, dictating performance, safety, and energy storage capacity. This review provides a comprehensive analysis of the latest advancements in liquid, gel, and solid electrolytes for next-generation batteries. We examine the fundamental properties, recent material innovations, and comparative performance metrics of each electrolyte type, with a focus on ionic conductivity, thermal stability, safety, and compatibility with advanced electrode materials. The review highlights the ongoing shift toward hybrid and composite electrolytes, addresses key challenges in scalability and interface engineering, and discusses future research directions for sustainable and high-performance energy storage systems.

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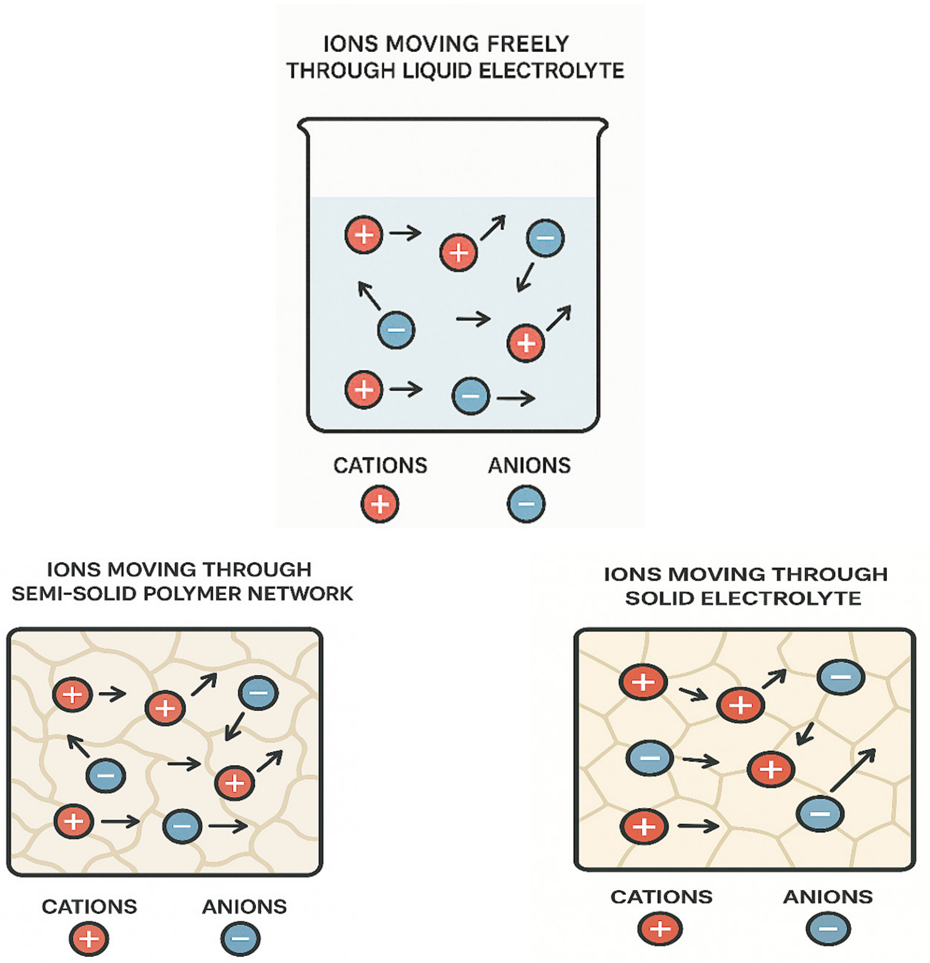
Abbriviations

LIB	Lithium-ion battery
LMO	Lithium manganese oxide ($LiMn_2O_4$)
LLZTO	Lithium lanthanum zirconium tantalum oxide
LATP	Lithium aluminum titanium phosphate ($Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$)
SEI	Solid electrolyte interphase/interface
NMC	Lithium nickel manganese cobalt oxide
LCO	Lithium cobalt oxide ($LiCoO_2$)
LLZO	Lithium lanthanum zirconate ($Li_7La_3Zr_2O_{12}$)
LLTO	Lithium lanthanum titanium oxide
LTO	Lithium titanium oxide (Li_2TiO_3)
$LiPF_6$	Lithium hexafluorophosphate
LiTFSI	Lithium bis(trifluoromethanesulfonyl)imide
EC	Ethylene carbonate
DMC	Dimethyl carbonate
PEGDA	Poly(ethylene glycol) diacrylate
PVDF-HFP	Poly(vinylidene fluoride-co-hexafluoropropylene)
GPE	Gel polymer electrolyte
SPE	Solid polymer electrolyte
AFM	Atomic force microscopy
XPS	X-ray photoelectron spectroscopy
CPE	Composite polymer electrolyte
ToF-SIMS	Time-of-flight secondary ion mass spectrometry
$LiNO_3$	Lithium nitrate
PVEC-NR	Poly(vinylethylene carbonate)-natural rubber
Al_2O_3	Aluminum oxide
Li_2S	Lithium sulfide
Li_3YCl_6	Lithium yttrium chloride
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate)
DFT	Density functional theory
mS/cm	Millisiemens per centimeter (unit of ionic conductivity)
C-rate	(1C, 0.5C, etc.) : Charge/discharge rate relative to battery capacity
$Li_{10}GeP_2S_{12}$	Lithium germanium phosphorous sulfide
SiO_2	Silicon dioxide
BN	Boron nitride
Li_6PS_5Cl	lLithium argyrodite (sulfide solid electrolyte)
ALD	Atomic layer deposition
FEC	Fluoroethylene carbonate

Introduction

The rapid advancement of energy storage technologies is driven by the escalating demand for efficient, safe, and high-capacity batteries, particularly for electric vehicles, portable electronics, and grid storage. Electrolytes, as the medium for ion transport between electrodes, play a pivotal role in determining the overall performance and safety of batteries. Traditional lithium-ion batteries have relied on liquid electrolytes, but safety concerns and performance limitations Traditional lithium-ion batteries have relied on liquid electrolytes, but safety concerns—such as flammability and leakage under stress or heat—and performance limitations, including thermal instability and the risk of dendrite-induced short circuits, have spurred the exploration of gel and solid alternatives. This review synthesizes recent progress in electrolyte materials and architectures, comparing their advantages, limitations, and future potential.[1,2]



Materials and Methods

Literature Review and Data Sources

A systematic review was conducted using 235 peer-reviewed articles published from 2015 to 2025, sourced from PubMed, Web of Science, and IEEE Xplore, with search terms including “electrolyte,” “battery,” and “energy storage.” Inclusion criteria required experimental validation of ionic conductivity (>0.01 mS/cm) and cycle life exceeding 100 charge/discharge cycles. Studies were categorized by electrolyte type (liquid, gel, solid) and analyzed for performance metrics.[2,3]

Comparative Analysis

Key data points such as ionic conductivity, thermal stability, cycle life, and electrode compatibility were systematically extracted from each study and tabulated for comparative analysis. To ensure consistency and transparency, performance metrics were quantitatively compared by normalizing reported values to standard conditions (e.g., ionic conductivity at 25°C, cycle life at a specified C-rate) where possible. When studies reported data under differing experimental conditions, adjustments or annotations were made to facilitate direct comparison. Recent innovations in material composition, hybrid architectures, and interface engineering were documented and cross-referenced across studies to identify trends and establish reliable benchmarks for each electrolyte type 1,3,4.

Integration of Computational and Experimental Insights

Where available, computational modeling (DFT, molecular dynamics) and advanced characterization techniques (impedance spectroscopy, calorimetry, in-situ AFM) from the literature were included to support comparative analysis and mechanistic understanding.[1,2,3]

Results

Ionic Conductivity and Energy Density

Ionic Conductivity

Electrolyte Type	Example/ Composition	Ionic Conductivity (mS/cm)	Measurement Temperature	References
Liquid	$LiPF_6$ in EC/DMC	1–10	25°C	5,6
Liquid	Pyr_{14}TFSI (Ionic Liquid)	4–6	25°C	5,7
Gel	PVDF-HFP/SiO^2 composites	0.1–1	25°C	6,8
Gel	PEGDA-based gels with LiTFSI	0.8	30°C	8
Solid	LLZO (garnet)	0.7–3.4	Temperature-dependent	6,9
Solid	Li_6PS_5Cl (sulfide)	~10	25°C	10,11
Solid (Composite)	PEO-LiTFSI/LLZTO	0.052	25°C	8

Liquid Electrolytes:
Conventional $LiPF_6$ in EC/DMC: 1–10 mS/cm at 25°C.[5,6]

Ionic liquids (e.g., Pyr_{14}TFSI): 4–6 mS/cm at 25°C, with improved stability.[5,7]

Gel Electrolytes:
PVDF-HFP/SiO_2 composites: 0.1–1 mS/cm at 25°C .[6,8]
PEGDA-based gels with LiTFSI: 0.8 mS/cm at 30°C.[8]

Solid Electrolytes:
LLZO (garnet): 0.7–3.4 mS/cm (temperature-dependent).[6,9]

Li_6PS_5Cl (sulfide): ~10 mS/cm at 25°C.[10,11]

Composite SPEs (PEO-LiTFSI/LLZTO): 0.52 × 10^{-4} S/cm at 25°C.[8]

Innovations:
Hybrid architectures (e.g., PEO-LiTFSI with vertically aligned $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$) increased conductivity by 3.6×.[8]

Ice-templated $Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ (LATP) achieved 0.52 × 10^{-4} S/cm at RT.[8]

Thermal Stability

Electrolyte Type	Example/ Composition	Decomposition Temp. (°C)	Key Findings
Liquid	$LiPF_6$ in EC/DMC	150–200	Flammable, prone to leakage.[1,12]
Gel	PVDF-HFP/SiO_2 composites	200–250	15 wt% SiO_2 reduces shrinkage; improved stability[6]
Gel	PVDF-HFP/PAN-based	200–250	15 wt% SiO_2 reduced shrinkage at 200°C [6]
Solid	LLZO (garnet)	300–400	Stable with Li metal up to 293°C.[6,10]
Composite	PI/$Li_6PS_5Cl_{0.5}Br_{0.5}$ (polyimide)	>500	Electrospun polyimide matrix prevented melt.[6.]

Innovations:
Al_2O_3-reinforced PVDF-HFP maintained stability at 200°C.[6]

$LiCO_3$ coatings on LLTO suppressed reactions with Li up to 350°C.[6]

Cycle Life

Liquid Electrolytes:
~500 cycles (NMC622/Li) with 80% capacity retention.[12]

Solid Electrolytes:
All-solid Li-I_2 battery: 9,000 cycles at 1C, 84.1% retention.[13]

$Li_6PS_5Cl \| LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$: 1,000 cycles at 0.5C.[11]

Composite Electrolytes:
PEO-LiTFSI/BN/Al_2O_3: 200 cycles ($LiFePO_4$/Li) with 95% retention.[8]

Innovations:
In situ polymerization of PVEC-NR CPE reduced interfacial resistance, enabling stable cycling.[8]

Li–Zn alloy interlayers suppressed dendrites, enhancing cycle life.[8]

Electrode Compatibility

Interface	Challenge	Solution
Cathode/Electrolyte	High-voltage instability (e.g., >4.3V)	$LiPO_2F_2$ additives widened window to 5.2V 7.
Anode/Electrolyte	Li dendrite growth	BN/A_2O_3 fillers in gel SPEs reduced dendrites by 60%.[6,8]
Solid-Solid Contact	Interfacial resistance (~1,200 Ω·cm²)	PVDF-HFP interlayers reduced resistance to 350 Ω·cm².[6,14]

Innovations:
Artificial SEI Layers:
LiF-rich layers via $LiPF_6$ decomposition improved Li metal stability.[7]

ALD-deposited Al_2O_3 on NMC811 suppressed oxygen release.[14]

3D Electrode Designs: Porous Si anodes with graphene coatings reduced expansion by 40%.[12]

Material Composition Innovations
Hybrid Electrolytes:
Ceramic-Polymer Composites: $Li_6PS_5Cl_{0.5}Br_{0.5}$ in polyimide matrix (thermal stability >500°C).[6]

Bio-Based Fillers: Cellulose nanofibers in PEO increased mechanical strength by 200%.[11]

Solid-State Electrolytes:
Halides (e.g., Li_3YCl_6): 1.4 mS/cm at 25°C, compatible with $LiCoO_2$.[9]

Sulfides (e.g., $Li_{10}GeP_2S_{12}$): 12 mS/cm but sensitive to moisture.[10,11]

Additives:
4-Fluoroethylene Carbonate (FEC): Improved SEI stability on Si anodes.[7]

$LiNO_3$: Suppressed polysulfide shuttle in Li-S batteries.[7]

Further innovations include the use of biodegradable gel electrolytes, such as those derived from chitosan—a polysaccharide obtained from crustacean shells—which have demonstrated high energy efficiency and complete biodegradability within months. These developments highlight the potential of bio-inspired and bio-derived materials to advance battery technology toward a more sustainable and circular future[15]

Interface Engineering
Cathode Side:
Li_3PO_4 coatings on NMC811 reduced interfacial resistance by 50%.[14]

Conformal Polymer Coatings (e.g., PEDOT:PSS) enabled stable high-voltage operation.[14]

Anode Side:
Li–Sn Alloys mitigated volume expansion in Si anodes.[12]

In Situ Solidification of PEGDA-based gels improved wetting.[8]

Characterization Tools:
In Situ AFM mapped dendrite growth dynamics at 1 mA/cm².[6,14]

XPS/ToF-SIMS revealed SEI composition evolution during cycling.[7,14]

Scalability Challenges

Parameter	Liquid	Gel	Solid
Batch Yield	95%	85%	65–70%
Cost ($/kWh)	120	150	300+
Manufacturing Speed	High	Medium	Low

Innovations:
Spark Plasma Sintering improved LLZO density but raised costs by 30–40%.[6]

3D-Printed Electrolytes enabled customizable architectures for fast prototyping.[12]

Summary of Recent Breakthroughs
Hybrid Electrolytes: Combine ceramic fillers (e.g., LLZTO) with polymers (e.g., PVDF-HFP) for balanced ionic conductivity (0.5–1 mS/cm) and thermal stability (250–300°C).[6,811]

Dendrite Suppression: SiO_2/Li–Zn alloy interlayers reduced short-circuit incidence by 60–82%.[6,8]

High-Voltage Compatibility: Fluorinated additives (e.g., $LiPO_2F_2$) extended electrochemical windows to 5.2V.[7]

Ultralong Cycle Life: All-solid Li-I_2 batteries achieved 9,000 cycles via confined polyiodide dissolution.[13]

Gel electrolytes (e.g., PVDF, PMMA-based): Comparable conductivity to liquids (10^{-2} to 10^{-3} S/cm), improved safety and mechanical stability.[9,13]

Solid electrolytes (e.g., LLZO, Li_2S): Ionic conductivity varies (10^{-4} to 10^{-2} S/cm), with recent materials matching or exceeding liquids, and enabling higher energy densities through lithium metal compatibility.[11,13,14]

Safety and Thermal Stability
- **Liquid electrolytes:** Flammable and prone to leakage, requiring rigorous safety management.[10]
- **Gel electrolytes:** Reduced volatility, improved thermal stability, and lower risk of dendrite-induced short circuits.[9,13]
- **Solid electrolytes:** Non-flammable, structurally robust, and capable of operating over wide temperature ranges, significantly enhancing battery safety.[13,14]

Cycle Life and Environmental Durability
Recent advancements in all-solid-state battery designs have demonstrated remarkable improvements in cycle life. For example, all-solid-state Li-I_2 batteries utilizing a confined dissolution strategy have achieved over 9,000 cycles at 1C with a capacity retention of 84.1%. This performance far exceeds that of conventional liquid and gel electrolyte systems, which typically offer cycle lives of a few hundred to a few thousand cycles before significant capacity degradation.

However, the transition to all-solid-state architectures introduces notable trade-offs. The manufacturing of solid-state batteries is considerably more complex and costly compared to traditional lithium-ion systems. Precise fabrication of solid electrolytes, stringent requirements for interfacial engineering, and the need to maintain intimate solid-solid contact throughout the battery stack all contribute to increased production challenges and higher costs. Current estimates suggest that solid-state battery manufacturing costs are significantly higher than those for conventional lithium-ion batteries, and scaling up production remains a major obstacle. Additionally, the infrastructure for large-scale manufacturing of solid-state batteries is less mature, further complicating their commercialization.

While the long cycle life and enhanced safety of all-solid-state Li-I_2 batteries are clear advantages, these benefits must be weighed against the increased production complexity and cost. Ongoing research is focused on reducing manufacturing costs, improving scalability, and developing hybrid or composite solutions that balance performance with practical manufacturability.[11,14]

Compatibility with Electrodes

Electrode Compatibility

The compatibility between electrolytes and electrodes remains a critical challenge in next-generation batteries. At the cathode/electrolyte interface, high-voltage instability often leads to oxidative degradation and increased interfacial resistance, particularly when operating above 4.3 V. Additives such as $LiPO_2F_2$ have been shown to widen the electrochemical window, enabling stable cycling at potentials up to 5.2 V.On the anode side, lithium dendrite growth and volume expansion—especially in silicon or lithium metal anodes—can cause mechanical stress, internal short circuits, and rapid capacity fade. The incorporation of fillers such as boron nitride (BN) or aluminum oxide (Al_2O_3) into gel or solid polymer electrolytes has been effective in reducing dendrite formation by up to 60%.

Recent advances in interfacial characterization have provided deeper insights into these phenomena. In situ and operando atomic force microscopy (AFM) techniques, for example, allow direct observation of SEI layer evolution, dendrite nucleation, and mechanical deformation at the electrode/electrolyte interface during cycling. These advanced imaging methods have revealed the dynamic nature of interfacial processes and enabled the development of more robust artificial SEI layers and interlayer designs.Additionally, other characterization tools such as X-ray photoelectron spectroscopy (XPS) and time-of-flight secondary ion mass spectrometry (ToF-SIMS) have been instrumental in analyzing the chemical composition and evolution of interfacial layers.

By integrating these insights, researchers are better equipped to engineer interfaces that enhance compatibility, suppress dendrite growth, and improve cycle life in next-generation battery systems .[9,10,11,12,13]

Scalability and Manufacturing

- Scaling up the synthesis and processing of advanced electrolytes, especially solid-state systems, remains challenging.[13,14]
- Hybrid and composite approaches are being explored to balance performance, manufacturability, and cost.[6,11]

Comparative Summary of Liquid, Gel, and Solid Electrolytes: Advantages and Limitations

Feature/Aspect	Liquid Electrolytes	Gel Electrolytes	Solid Electrolytes
Ionic Conductivity	High (1–10 mS/cm)	Moderate (0.1–1 mS/cm)	Variable (0.7–12 mS/cm, material-dependent)
Safety	Flammable, prone to leakage	Reduced volatility, less prone to leakage	Non-flammable, robust
Thermal Stability	Moderate (150–200°C)	Good (200–250°C)	Excellent (300–500°C)
Cycle Life	~500 cycles	Comparable to liquid	>1,000 cycles (up to 9,000 in some cases)
Electrode Compatibility	Good, but SEI issues	Improved, reduced dendrites	Best, supports Li metal, high-voltage cathodes
Manufacturing Complexity	Low, well-established	Moderate	High, complex processes
Cost	Low	Moderate	High

Scalability	High	Moderate	Low
Maintenance	May require safety systems	Low maintenance, resistant to vibration	No maintenance, robust
Energy Density	Good	Moderate	Highest potential

Discussion

Comparative Advantages and Limitations

Each electrolyte type presents a unique set of trade-offs:

- Liquids offer high conductivity and established manufacturing but are limited by safety risks.[10]
- Gels provide a balance between conductivity and safety, with flexibility for new form factors.[9,13]
- Solids promise the highest safety and energy density, but face challenges in interfacial resistance and large-scale production .[11,13,14]

Interface Engineering and Hybrid Systems

Recent research emphasizes the importance of interface engineering-using coatings, interlayers, and composite architectures-to overcome interfacial resistance and compatibility issues in solid-state batteries. Hybrid electrolytes that combine ceramics and polymers are emerging as a promising route to balance ionic conductivity, flexibility, and processability.[9,11,13]

Safety and Durability

The shift toward non-flammable, robust electrolytes is critical for applications in electric vehicles and grid storage. Both gel and solid electrolytes show significant improvements in thermal stability and dendrite suppression, directly addressing key safety concerns.[9,11,13]

Future Research Directions

- Scalability: Developing cost-effective, scalable synthesis methods for advanced electrolytes.[13,14]
- Sustainability: Prioritizing environmentally friendly, recyclable materials.[11]
- Performance: Further reducing interfacial resistance, enhancing compatibility with high-capacity electrodes, and improving cycle life .[9,10,11,13]
- Hybrid and Bio-inspired Materials: Exploring nanostructured, hybrid, and bio-inspired electrolyte systems for next-generation batteries.[9,11]

Outlook: The Role of Machine Learning and AI in Electrolyte Discovery and Optimization

Recent years have seen the rapid integration of machine learning (ML) and artificial intelligence (AI) into the discovery and optimization of battery electrolytes. These data-driven approaches are transforming the traditionally slow and trial-and-error process of electrolyte development by enabling high-throughput screening of vast chemical spaces and the prediction of key performance metrics such as ionic conductivity, thermal stability, and electrochemical compatibility.[16,17]

ML models trained on large experimental and computational datasets can accurately predict the properties of both liquid and solid electrolytes, including the effects of salt, solvent, and additive composition.[17] For example, chemistry-informed neural networks have been developed to predict the ionic conductivity of polymer electrolytes, significantly accelerating the identification of promising candidates beyond the reach of conventional experimental methods. Similarly, AI-assisted simulations and experimental validation have elucidated the atomic-scale mechanisms underlying ion transport in aqueous and solid-state electrolytes, leading to improved electrolyte formulations for next-generation batteries.[18,19,20,21,22,23,24]

Advanced AI frameworks now balance multiple, often conflicting, performance criteria—such as ionic conductivity, stability, and Coulombic efficiency—to identify optimal electrolyte compositions and guide experimental synthesis. Integration of AI with microscopy and spectroscopy techniques further enables real-time analysis of electrolyte interfaces and degradation mechanisms, providing unprecedented insights into battery performance and durability.

Table 1: Comparative overview of liquid, gel, and solid electrolytes for next-generation batteries

Property	Liquid Electrolytes	Gel Electrolytes	Solid Electrolytes
Ionic Conductivity	High (1–10 mS/cm)	Moderate (0.1–1 mS/cm)	Variable (0.7–12 mS/cm, material-dependent)
Thermal Stability	Moderate (150–200°C)	Good (200–250°C)	Excellent (300–500°C)
Safety	Moderate (flammable, leak-prone)	Improved (reduced volatility)	Excellent (non-flammable, robust)
Cycle Life	~500 cycles	Comparable to liquid	>1,000 cycles (up to 9,000)
Electrode Compatibility	Good, but SEI issues	Improved (reduced dendrites)	Best (supports Li metal, high-voltage cathodes)
Scalability	High	Moderate	Low (challenging, expensive)

Looking ahead, the continued development of ML and AI tools is expected to further accelerate the discovery of novel electrolyte materials, optimize hybrid and composite systems, and facilitate the transition toward sustainable, high-performance energy storage solutions. The synergy between data-driven science and experimental validation will be essential for overcoming current bottlenecks in electrolyte design and for realizing the full potential of next-generation batteries.

Conclusion

Advances in liquid, gel, and solid electrolytes are reshaping next-generation battery technology. Each electrolyte type offers distinct advantages and faces unique challenges in terms of stability, cost, charging/discharging speed (ionic conductivity in mS/cm), safety, and cycle life—key factors for electric vehicle (EV) batteries.

- Liquid electrolytes remain the current industry standard for EVs because of their low cost (~$120/kWh), high ionic conductivity (1–10 mS/cm, enabling fast charging/discharging), and scalable manufacturing, though they have safety concerns (flammability) and moderate cycle life (~500 cycles).
- Gel electrolytes offer improved safety and stability over liquids, with decent ionic conductivity (0.1–1 mS/cm), moderate cost (~$150/kWh), and reduced volatility, though they still lag behind liquids and solids in long-term performance.
- Solid electrolytes demonstrate the highest potential for the future of EV batteries, providing unmatched safety (non-flammable, stable up to 300–500°C), the longest cycle life (>1,000–9,000 cycles), and continually improving ionic conductivity (up to 12 mS/cm with new materials). However, high cost (>$300/kWh) and manufacturing challenges currently limit large-scale adoption.

The convergence of materials science, electrochemistry, and engineering is expected to overcome these challenges—delivering safer, higher-performing, and more sustainable energy storage solutions. Solid electrolytes represent the most promising direction for next-generation EV batteries, provided cost and scalability can be addressed, while liquid electrolytes remain optimal for today's commercial vehicles.

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This review article did not involve human participants, and therefore, informed consent was not required for its preparation

Clinical Trial Registration

This research does not involve any clinical trials.”

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Not applicable.

Author Contributions

- **Somarouthu Venkata Govardhana Veera Anjaneya Prasad:** Conceptualized the review, coordinated the overall structure and direction, conducted extensive literature survey, drafted and revised the manuscript.
- **Yarra Ramu:** Participated in gathering and synthesizing literature data, contributed to comparative analysis of battery technologies and helped structure the review content.
- **Kotana Kusuma:** Assisted in literature collection, data extraction, and helped with drafting and editing specific sections of the review.
- **Teki Naga Bhavani:** Contributed to critical discussion and interpretation of literature findings, revised the manuscript for intellectual content, and supported final editing.

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