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Principles and Requirements of Battery Electrolytes: Ensuring Efficiency and Safety in Energy Storage

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ABSTRACT

Electrolytes lie at the heart of every battery, serving as the medium that allows ions to move between electrodes and enabling energy to be stored and released efficiently. Their properties, such as ionic conductivity, electrochemical stability, and thermal resilience, directly shape the performance, safety, and lifespan of energy storage systems. As demand for reliable batteries grows in electric vehicles, renewable energy integration, and portable devices, the design of better electrolytes has become a critical research priority. This review brings together insights from a wide range of studies to examine the principles, requirements, and limitations of five major electrolyte systems: aqueous, organic, ionic liquid, solid-state, and redox-active types. Each category demonstrates clear strengths but also important trade-offs. Aqueous electrolytes remain affordable and eco-friendly yet struggle with narrow voltage windows. Organic systems deliver high energy density but introduce flammability concerns. Ionic liquids promise exceptional stability but remain expensive and viscous. Solid-state electrolytes enhance safety and energy density, though they face manufacturing and conductivity challenges. Redox-active systems stand out for durability and scalability, particularly in grid-level applications, but lack compactness. Taken together, the findings emphasize that no single solution is universal. Instead, electrolyte design must be tailored to the context, balancing performance, safety, cost, and sustainability.

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INTRODUCTION

Electrolytes play a pivotal role in the operational core of batteries, functioning as the medium that enables ion transport and energy conversion. These vital components power a wide range of modern technologies, from consumer electronics to renewable energy systems and life-support devices. Chemically diverse, electrolytes range from aqueous solutions to solid-state materials, each tailored to specific technological applications. Their fundamental characteristics, such as ionic conductivity, electrochemical stability, and thermal sensitivity, directly determine battery performance and safety (Ramachandran & Wang, 2018).

Despite their central role, electrolytes face inherent challenges that complicate the optimization of battery systems. Ionic conductivity dictates the speed of ion transfer, influencing charge and discharge cycles (Joia et al., 2024) while the electron exchange process involving hydrogen cations reflects the delicate nature of electrochemical reactions (Boz et al., 2021). Electrochemical stability ensures prolonged battery life, but temperature sensitivity limits the operating range of many electrolytes (Balbuena, 2014). Furthermore, electrolytes must remain compatible with electrode materials and avoid unwanted side reactions that could destabilize the system (Borodin et al., 2017). These challenges underscore the need for a deeper exploration of electrolyte design and application.

Previous studies have examined the isolated properties of electrolytes in detail. Research has consistently emphasized ionic conductivity as a key performance factor, electrochemical stability as the basis for longer cycle life, and temperature sensitivity as a limiting factor in diverse operational environments. Likewise, compatibility with electrode materials has been studied as an essential safeguard against unwanted chemical interactions (Borodin et al., 2017). However, these studies often treat such factors independently, without integrating them into a holistic framework that reflects real-world applications.

The global shift toward electrification, renewable energy integration, and sustainable technologies has placed increasing pressure on the development of advanced battery systems (Taabodi et al., 2025). Electrolytes lie at the forefront of this transformation. Nevertheless, they must operate under multiple stressors, including extreme temperatures, varied electrode chemistries, and safety-critical environments such as those found in electric vehicles, grid-scale storage, and medical devices (Nagarajan et al., 2025). The challenge is not only to optimize electrolyte performance in laboratory conditions but also to ensure reliability and durability in real-world applications where complex and dynamic conditions prevail (Shah et al., 2024).

The following central research question guides this study: To what extent does electrolyte battery compatibility influence the performance, safety, and durability of energy storage systems across diverse applications such as consumer electronics, electric vehicles, renewable energy integration, and medical devices?

Although significant advances have been made in characterizing individual electrolyte properties, an integrative perspective on their compatibility with diverse real-world battery applications remains underexplored. Most studies continue to focus on conductivity, stability, or thermal sensitivity in isolation, without adequately considering how these characteristics interact across different battery chemistries and application environments. This limitation restricts the translation of laboratory findings into practical, scalable energy storage systems. By addressing electrolyte battery compatibility with diverse real-world applications, this study, as a central theme, seeks to bridge the gap, contributing to the design of more reliable, durable, and application-specific battery technologies that can meet the growing global demand for sustainable energy storage solutions.

METHODS AND MATERIALS

This review paper draws upon an informative and formulated search in the literature with respect to the subject. A qualitative methodology was employed to synthesize the multifaceted sources, including peer-reviewed journal articles, academic books, institutional reports, and credible grey literature. The literature search has been achieved using academic databases, including Google Scholar, JSTOR, Scopus, PubMed, and ScienceDirect, by means of a combination of keywords and Boolean operators' combination to narrow down the results. Only English-published sources accessible during a specific time range were taken into consideration, and the focus was on the sources presenting the major themes of a review directly. Such inclusion and exclusion criteria were used to guarantee academic rigor and relevance. Research papers would be incorporated in the literature review when they revealed some empirical or theoretical knowledge and displayed a certain sense of methodological rigor attached to the subject of study, and made some contributions to existing discussions or findings in the research community. The sources, which did not undergo peer review or contained extraneous information that was inaccessible in full text, were also excluded. The literature was then synthesized by reviewing the gathered information, and key points were extracted and tabulated under relevant themes.

Function of Electrolyte

The role of the electrolyte in a battery is indeed to supply so-called ions (that is just an abbreviation for electrons) between cathode and anode to permit these two substances or poles, electrical energy generators themselves, to react on each other. This creates a conventional hydrogenation current in one direction until it materializes. It also serves as a medium, allowing ions to flow from one electrode to the other while charging and during discharging (Hamed et al., 2022). Figure 1 illustrates the schematic function of an electrolyte in an electrical energy storage system.

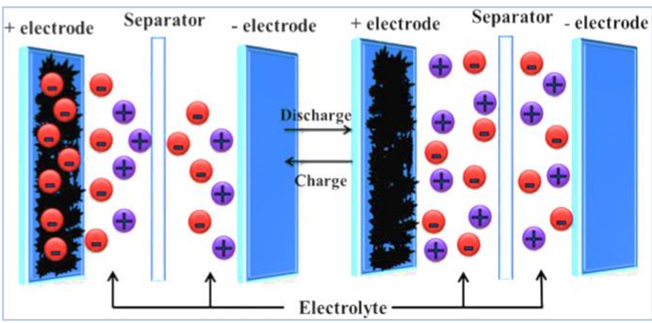

Figure (1). *Electrolyte ions distribution behavior during charging and discharging of electrochemical supercapacitor(Chennupati Jagadish, Robert Hull, 2020).*

Fundamentally, the electrolyte functions as a modulator for ionic transfer, producing an environment with conduction capability inside the battery (Zhong et al., 2016). The flow of ions is essential because ion movement forms an integral part in the process, graphically depicted by chemical formulas, whereby energy captured as chemistry must be converted into usable electrical energy. Thus, according to the operating principle behind them and how such batteries are meant to be used, all sorts of different electrolyte formulations may have been developed. Some are suitable as alkaline solutions, or others with chemical compositions that may vary from one type of battery design to another (Chattopadhyay et al., 2023).

Characteristics of Electrolyte

The electrolyte functions as a conductive compound, facilitating conduction when dissolved in a water solution, in a molten state, or in solid form. It can dissociate into free-moving ions upon dissolution in water, heating, or it can easily carry the ions between two opposite electrodes in solid-state electrolytes. In batteries, the electrolyte plays a pivotal role in ion transportation and current conduction between the positive and negative electrodes (Boz et al., 2021).

As the primary material in lithium-ion batteries, the electrolyte significantly shapes the battery's specific energy, lifespan, safety performance, and rate capability (Li et al., 2016). A practical electrolyte for lithium-ion batteries should adhere to the following criteria:

High Ionic Conductivity: While lacking electronic conductivity, the electrolyte must exhibit robust ion conductivity, typically between 1×10^{-3}~2×10^{-3}S/cm within a specific temperature range (Hua et al., 2020). It requires excellent ion conductivity and electronic insulation to serve as an effective ion transport medium while minimizing self-discharge (Yang & Wu, 2022). Figure 2 shows the relationship between ionic conductivity and the potential window of different electrolytes.

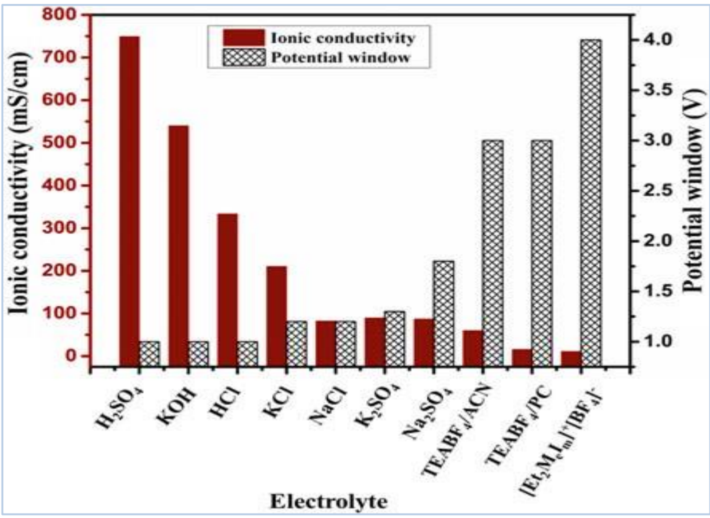

Figure (2). *The ionic conductivity window of some Aqueous electrolytes (Jagadish & Hull, 2020)*

High Ion Migration Number: The transportation of charges in a lithium-ion battery relies on ion migration. A high ion migration number, approaching 1, reduces concentration polarization during electrode reactions, contributing to high energy and power densities (Borodin et al., 2017).

Chemical and Thermal Stability: When in direct contact with the electrode, the electrolyte should minimize side reactions, necessitating a certain level of chemical and thermal stability (Il'ina et al., 2020; Tron et al., 2022).

Mechanical Strength: The electrolyte in batteries should possess adequate mechanical strength to meet the demands of large-scale production and packaging processes (Armand & Tarascon, 2008). Additives, such as trimethyl phosphate (TMP), can enhance the battery's rate capability and cycling performance (Zheng et al., 2018).

Excellent Mechanical Performance: As the electrolyte directly interfaces with positive and negative electrodes, polymer lithium-ion battery electrolytes require robust toughness to withstand stress variations during battery assembly, storage, and usage, avoiding brittleness (Howarth et al., 2016). Simultaneously, as a separator, it should have sufficient mechanical strength to suppress the formation and piercing of lithium dendrites, preventing short circuits between positive and negative electrodes (Zhou et al., 2019).

Totally, battery electrolytes must align with the characteristics outlined in Table 1, adhering to rigorous criteria such as high ionic conductivity, seamless compatibility with anode and cathode electrodes, superior chemical and thermal stability, and a non-toxic composition to increase overall safety (Howarth et al., 2016).

Table 1. *Important features of battery electrolytes*

Primary features	Secondary features	Tertiary features
High potential window	Low viscosity	Environmentally friendly
High ionic conductivity	Low cost	Easy to handle
Small-sized hydrated ions	High chemical stability	Easily available
High capacitance	Low volatility	Nontoxic
Large operating temperature range	Non-flammability	
No electric conductivity	Optimum concentration	
Non-reactivity with electrode materials		

Table (1). Illustrate the characteristics of electrolytes (Li et al., 2016).

Type of Electrolyte

Electrolytes are typically categorized by their physical state, including both liquid and solid forms. Additionally, their classification spans five categories, considering both chemical and physical structures: aqueous (Chen et al., 2022), organic (Chen et al., 2020), ionic liquids (Yang & Wu, 2022), solid state or quasi-solid state (Kaus et al., 2021), and redox-active electrolytes (Jagadish & Hull, 2020).

Aqueous Electrolytes

In aqueous electrolytes, water serves as the solvent for salts, offering superiority over organic electrolytes in terms of environmental impact, ionic conductivity, electrochemical behavior, open atmosphere handling, and cost-effectiveness. Despite these advantages, aqueous electrolytes possess a limited potential window compared to organic and ionic liquid (IL) counterparts. With a thermodynamic potential window of 1.23, water can be electrolyzed into hydrogen and oxygen at a low potential window (Chen et al., 2020). While aqueous electrolytes demonstrate high conductivity and capacitance, their potential window typically ranges from 1.0 to 1.5 V, with the possibility of reaching 2.0 V using neutral aqueous electrolytes like Na2SO4 and KCl. The commercial application of aqueous electrolytes is restricted due to this low potential window; however, they remain cost-effective and easy to fabricate compared to organic electrolytes (Armand et al., 2009). Electrolyte performance hinges on factors such as ion size, hydrated ion size, corrosive behavior, mobility, and ion conductivity. Aqueous electrolytes, chemically categorized as acidic, alkaline, and neutral, exhibit conductivity one order of magnitude higher than organic electrolytes (Chen et al., 2022).

Organic Electrolytes

Utilized in many battery types, organic electrolytes consist of organic solvents and are prevalent in batteries. This type of electrolyte is often made by incorporating of inorganic compounds like LiPF6, LiBF4, or LiClO4 with organic solvents like acetonitrile , propylene carbonate, hexafluoro isopropanol (Jagadish & Hull, 2020).

Ionic Liquid Electrolytes

Any salt in a liquid state at room temperature or below 100 °C qualifies as an ionic liquid (Chen et al., 2014). Typically, Ionic liquids are neutral at room temperature, yet their electrolytes contain free or paired ions. Unlike ionic liquid electrolytes, water in a liquid state lacks free or paired ions (Soloveichik, 2015). Ionic liquid electrolytes do not require additional solvents, offering high chemical stability due to the robustness of ionic bonds over van der Waals forces (Weber et al., 2011). An ionic liquid electrolyte is an organic salt in a liquid state at room temperature, garnering attention for its expansive potential window, exceptional thermal, electrochemical, and chemical stability, non-volatility, and low vapor pressure. Interestingly, ants introduced the concept of ionic liquid in nature (Miao et al., 2022). In a skirmish between tawny and fire ants, tawny ants release self-venom (formic acid) on their bodies to neutralize the fire ant's venom (alkaloid-based venom), forming the first known ionic liquid electrolyte (Chen et al., 2014).

Solid-State Electrolytes

In contrast, electrolytes boast high ionic conductivity; however, the challenge of electrolyte percolation remains significant. The imperative for flexible electronic devices, including printed electronics, wearable tech, and microelectronics, has led to a heightened interest in solid-state electrolytes (Janek & Zeier, 2016). These electrolytes, whether solid-state in nature, not only serve as conductors but also act as separators in traditional applications(Francisco et al., 2012). Solid electrolytes facilitate seamless fabrication and packaging. In the hierarchy of chemical composition, solid electrolytes rank higher, while natural polymers like PE and inorganic solids in ceramic form hold a lower status. These materials, commonly used, provide good electrochemical stability at the expense of ionic conductivity. Solid electrolytes, along with solid-state counterparts, are materials capable of volume change, contributing to device flexibility.

Additionally, electrolytes of the same type exhibit commendable mechanical strength (Yang & Wu, 2022). The solid electrolytes are divided into the main types (inorganic and polymer electrolytes), see *Figure 3*. The polymer electrolytes can be further classified into three categories: solid/dry polymer electrolytes, gel polymer electrolytes, and polyelectrolytes, and the inorganic part is divided into two sulfide and oxide types.

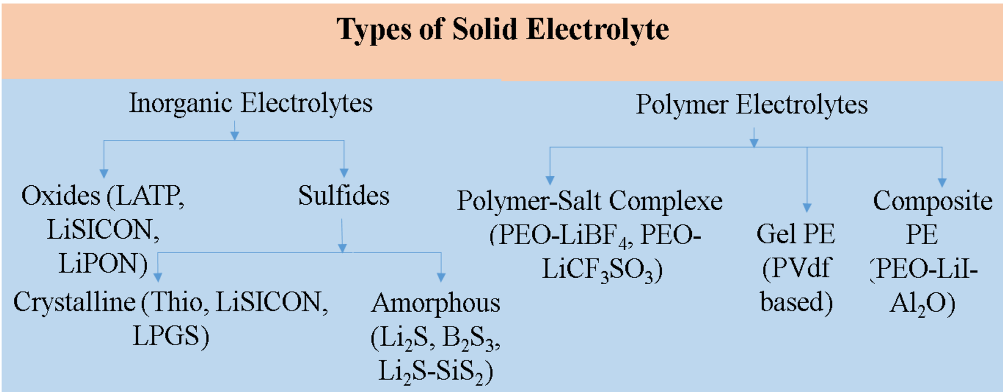

Figure 3. *Schematic illustration of solid-state electrolyte types. (Karabelli Kaus et al., 2021)*

Solid-state batteries offer a substantial advantage with higher energy density due to the use of a solid electrolyte, enabling the use of lithium metal as an anode (Ma et al., 2023). This can potentially double or triple battery energy density, leading to extended device lifespans and increased electric vehicle travel distances (Moradi et al., 2023). Safety benefits include a reduced risk of fire or explosion, as solid electrolytes are less flammable than liquid counterparts. Additionally, environmental impact is anticipated to be lower(Albertus et al., 2021). However, challenges exist. High production costs, attributed to the use of expensive materials and complex manufacturing processes, may hinder widespread adoption. Solid-state batteries also underperform in low temperatures, limiting their applicability in specific environments. Concerns about lifespan persist, despite the higher energy density, necessitating further research and real-world testing for a comprehensive understanding and successful integration of this promising technology (Moradi et al., 2023).

Redox-Active Electrolytes

The solid electrolyte commonly incorporates redox additives such as iodides (e.g., KI, NaI) and organic redox mediators like PPD and hydroquinone, or a combination of both. These redox-active electrolytes are typically dissolved into the gel polymer electrolyte, akin to organic and aqueous electrolytes (Yu et al., 2014). Gel polymer electrolytes, when coupled with redox-active mediators, exhibit significantly higher specific capacitance compared to non-redox-active mediator Gel Polymer Electrolytes (GPEs) (Ma et al., 2023). Commonly used polymers in gel polymer electrolytes include PVA, Nafion, and PEO. An example combination, KI–$VOSO_4$ with PVA/H_2SO_4, demonstrates notable performance, providing a high specific capacitance of 1232.8 F/g and an energy density of 25 Wh/kg(Khan, 2015). Each of these electrolyte types further encompasses various subtypes, each of which is suitable for specific battery applications, ensuring compatibility and optimal performance (Jagadish & Hull, 2020).

FINDINGS

This review highlights that electrolyte play a central role in the operation and advancement of modern energy storage systems. Their chemical and physical characteristics directly govern a battery's performance, safety, and suitability for different applications. The evaluation of five major electrolyte categories — aqueous, organic, ionic liquid, solid-state, and redox-active systems — reveals that while each possesses distinct advantages, none fulfills all performance criteria simultaneously (see T*able 2).* Instead, their utility is highly context-dependent, shaped by the balance between energy requirements, cost, safety, and environmental considerations. Aqueous electrolytes continue to play a vital role in conventional technologies such as lead-acid and nickel–cadmium batteries. Their strengths lie in low cost, high conductivity, and environmental friendliness, particularly in neutral pH formulations. Nevertheless, their narrow electrochemical stability window (~1.23 V) constrains energy density, and issues such as corrosion and evaporation limit long-term durability. Consequently, they are most suitable for stationary or low-voltage systems where affordability and sustainability are prioritized over high energy density.

Organic electrolytes, by contrast, dominate in lithium-ion batteries because of their wide voltage window (~4–5 V), which enables compact, high-energy storage. For more details, refer to *Table 2).* This makes them indispensable for portable electronics and electric vehicles. However, their volatility, flammability, and environmental unsustainability remain significant drawbacks. Their chemical instability at elevated temperatures and voltages also poses a challenge to their long-term performance. As such, while organic electrolytes are currently indispensable, their future is contingent on addressing safety and sustainability concerns. Ionic liquid electrolytes offer a promising alternative, combining non-volatility, wide electrochemical stability, and high thermal resistance. These properties make them inherently safer than conventional organic solvents. Nevertheless, their high viscosity slows ionic transport, while their elevated production costs hinder commercial competitiveness. Additionally, uncertainties remain regarding their environmental impact, which must be clarified before large-scale deployment can be justified.

Solid-state electrolytes (SSEs) represent perhaps the most ambitious frontier in electrolyte research. Their leak-proof, flame-resistant characteristics and compatibility with lithium metal anodes suggest transformative potential in both energy density and safety see *Table 2)*. Materials such as $Li_7La_3Zr_2O_{12}$ illustrate this promise. However, current limitations—including reduced ionic conductivity at room temperature, interfacial resistance with electrodes, high manufacturing costs, and structural rigidity—pose significant barriers to commercialization. Overcoming these hurdles would mark a significant step toward realizing safer, next-generation batteries. Redox-active electrolytes occupy a specialized but increasingly important niche, particularly in large-scale flow batteries. By storing energy through redox reactions, they permit the independent scaling of energy and power, offering exceptional durability and long cycle life. These traits make them well-suited for grid-level applications where stability and longevity are paramount. However, their relatively low energy density, combined with reliance on costly or environmentally sensitive materials, constrains their relevance for portable or high-demand devices.

Table 2. *Show important features of battery electrolytes*

Electrolyte Type	Key Advantages	Limitations / Challenges	Typical Applications
Aqueous	Low cost, high ionic conductivity, environmentally friendly (primarily neutral pH)	Narrow electrochemical window (~1.23 V), corrosion, evaporation, and limited energy density	Lead-acid batteries, nickel–cadmium batteries, and stationary or low-voltage systems
Organic	Wide voltage window (~4–5 V), high energy density	Volatile, flammable, environmental concerns, chemical instability at high temperature/voltage	Lithium-ion batteries, portable electronics, electric vehicles
Ionic Liquid (IL)	Non-volatile, high thermal and electrochemical stability, safer than organic solvents	High viscosity (low ionic mobility), expensive, uncertain environmental impact	High-stability batteries, potential next-generation systems
Solid-State Electrolytes (SSEs)	Leak-proof, flame-resistant, compatible with lithium metal, mechanically strong	Low room-temperature conductivity, interfacial resistance, high cost, and structural rigidity	Next-generation batteries, high-safety systems
Redox-Active	Independent scaling of power and energy, long cycle life, durable	Low energy density, reliance on costly or rare materials, and less suitable for compact devices	Large-scale flow batteries, grid-level energy storage

DISCUSSION

The finding of this review emphasizes that electrolytes are key to the performance, safety, and adaptability of modern batteries. However, no single system meets all operational requirements (*see Table 2*). This critical discussion compares our findings with broader insights from the literature. For instance, (Zhang et al., 2021) similarly reported that aqueous electrolytes remain dominant in cost-sensitive applications due to their high conductivity and sustainability. However, their narrow electrochemical stability window limits high-energy performance. Our findings corroborate this view, emphasizing that aqueous electrolytes are most appropriate for stationary and low-voltage applications.

Organic electrolytes, as confirmed in our analysis, continue to underpin commercial lithium-ion batteries owing to their wide voltage window. This aligns with the observations of (Yang et al., 2023), who noted that organic carbonate-based solvents remain unmatched in enabling compact, high-energy storage. However, like our findings, their study underscores the persistent drawbacks of volatility, flammability, and environmental unsustainability. Recent work on fluorinated and bio-derived solvents (Rao et al., 2024) attempts to address these issues, yet challenges in scalability remain unresolved.

The performance of ionic liquid electrolytes in our review also reflects results from recent experimental studies, which demonstrate superior safety and thermal stability but note hindered ionic mobility due to high viscosity (Armand et al., 2009). Similarly, Shah et al. (2024) highlighted the high production cost as a central obstacle, which mirrors the economic barriers identified in our analysis.

Solid-state electrolytes (SSEs) are widely regarded as the most promising next-generation candidates, and our findings reinforce this perspective. Wang et al. (2025) and Lee et al. (2024) have confirmed their superior safety profile and compatibility with lithium metal anodes. However, consistent with our review, these works also point to persistent interfacial resistance and limited room-temperature conductivity as barriers to commercialization.

The importance of redox-active electrolytes in large-scale energy storage, as highlighted in this review, is also reflected in recent studies on vanadium and organic flow batteries(Feng et al., 2025). While these technologies show promise in terms of scalability and cycle life, both our findings and existing literature point out a significant drawback: their low energy density. This limitation makes them less suitable for portable devices, where higher energy density is crucial. When we compare our findings with existing studies, it is evident that research on electrolytes has made significant strides. However, the field still faces some tough trade-offs. The similarities in results across various studies suggest that future advancements will hinge on adopting hybrid approaches, reducing costs, and using environmentally friendly materials. This balance is essential for achieving both high performance and practical use in the real world.

CONCLUSION

In this review article, we highlight the essential role that battery electrolytes play in improving the performance and safety of energy storage systems. Key features, such as high ionic conductivity, wide potential windows, and high chemical stability, are crucial for making batteries efficient and long-lasting. Additional factors such as low viscosity, affordability, non-toxicity, and a broad operating temperature range also contribute to their effectiveness. Next, we explore various types of electrolytes, including aqueous, organic, ionic liquids, solid-state, and redox-active electrolytes. In aqueous electrolytes, sulfuric acid (H_2SO_4) is commonly used in acidic batteries, while potassium hydroxide (KOH) is used in alkaline batteries. Sodium sulfate (Na_2SO_4) is chosen for neutral, environmentally friendly applications, making them ideal for stationary and low-voltage uses. Organic electrolytes are effective but face challenges in scaling up production. Ionic liquids (ILs) offer high voltage stability and thermal resilience, although they may have reduced ion mobility and can be costly. Solid-state electrolytes (SSEs) stand out for being leak-proof and safe. However, they encounter issues such as interfacial resistance and low conductivity at room temperature, which can limit their application. Gel polymer electrolytes (GPEs) balance conductivity and flexibility, making them an excellent option for wearable devices.

On the other hand, while redox-active electrolytes are promising for large-scale energy storage, their low energy density makes them less suitable for portable applications. No single electrolyte can meet all demands, so ongoing research is vital as the need for efficient energy storage rises. Future efforts will likely focus on hybrid formulations that enhance the effectiveness, safety, and sustainability of battery technologies.

AUTHORS CONTRIBUTIONS

- Reza Joia and Meiram Stamenov conceptualized and supervised the study.
- Naseer Mukhlis, Reza Joia, and Sayed Abdullah Hossaini collected the row data.
- Reza Joia wrote the manuscript with input from all authors.
- All authors reviewed and approved the final version.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest

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