Battery Electrolyte Formulation in Lithium-Ion Batteries: A Survey

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Abstract

Battery electrolyte formulation is a critical determinant of lithium-ion battery performance, safety, and longevity, influencing ion transport between the anode and cathode. This survey examines the complex interplay of electrolyte components—solvents, salts, and additives—highlighting their impact on ionic conductivity and electrochemical stability. Key advancements include localized high concentration electrolytes (LHCEs) and non-flammable gel polymer electrolytes, which enhance safety and performance by mitigating flammability risks and improving lithium-ion transport. Safety challenges such as thermal instability and dendrite formation necessitate innovative solutions to maintain battery integrity and extend operational lifespan. The development of stable solid electrolyte interphases (SEI) is emphasized for high-energy-density applications like lithium-sulfur batteries. Future research should prioritize molecular design optimization and novel electrolyte formulations to achieve superior thermal stability and safety. Additionally, exploring solid-state battery technologies and sustainable recycling methods will be crucial for cost-effective production. This survey underscores the importance of electrolyte innovation in advancing lithium-ion battery technology, addressing current challenges, and leveraging emerging trends to meet the growing demands of modern energy storage applications.

1 Introduction

1.1 Significance of Electrolyte Formulation

Electrolyte formulation is crucial for the performance and safety of lithium-ion batteries, facilitating ion transport between the anode and cathode, which directly influences cycle life and stability. The demand for higher energy density and safety in rechargeable batteries is underscored by challenges in developing multivalent-ion batteries with water-based electrolytes [1]. This formulation is essential for optimizing battery performance under varying conditions, such as low temperatures, significantly affecting both lithium-ion and sodium metal batteries.

The solubility of small organic materials in electrolytes can hinder gravimetric capacity, emphasizing the need for precise formulation [2]. The development of rechargeable zinc-air batteries (ZABs) further illustrates the necessity for innovative electrolyte formulations, particularly through near-neutral chloride electrolytes to enhance battery lifetime and performance [3]. Recent research suggests that exploring highly concentrated and non-standard electrolyte solutions could markedly improve energy storage performance and address challenges such as low-temperature operation and charge transport mechanisms [4, 5, 6, 7]. The incorporation of composite electrolytes is vital for improving power density, cycle life, and safety while ensuring environmental compatibility, which is essential for high-energy density batteries across various applications.

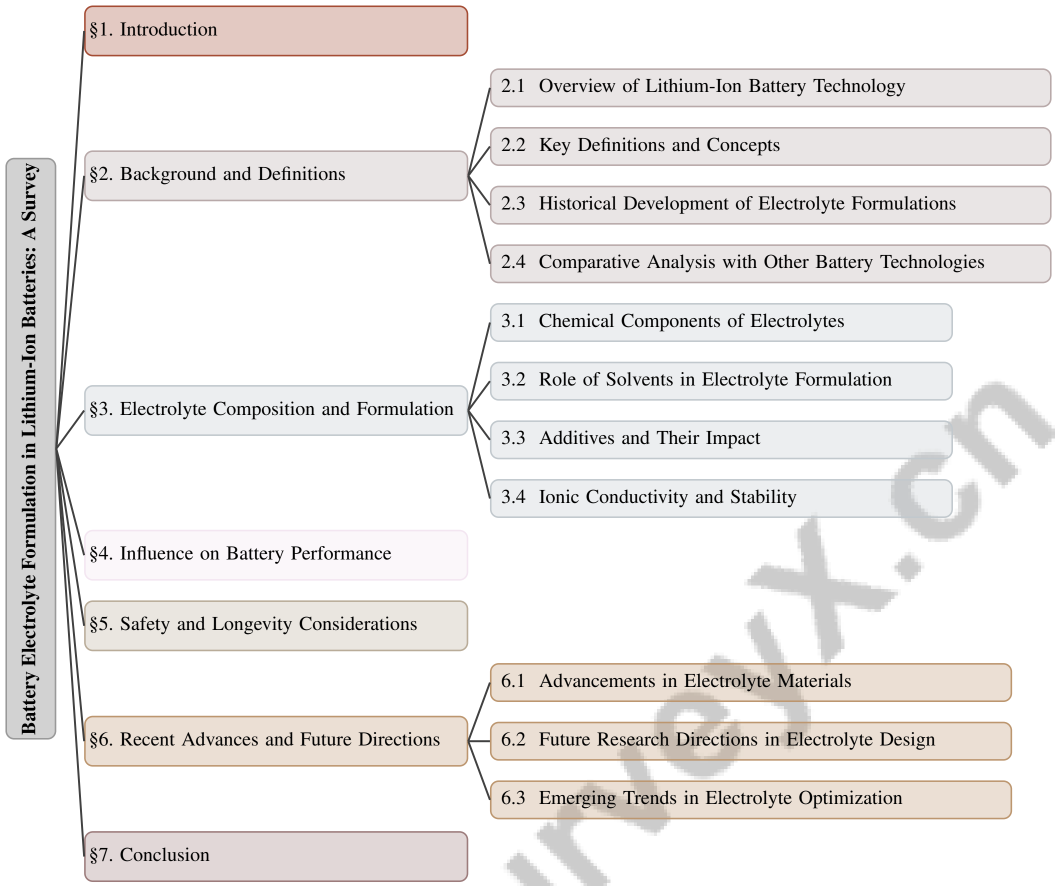

Figure 1: chapter structure

1.2 Role in Ion Transport

The role of electrolytes in ion transport is fundamental to lithium-ion battery functionality, directly affecting efficiency and overall performance. The electrolyte acts as a medium for lithium ion movement during charge and discharge cycles, essential for converting chemical energy to electrical energy. The complexity of ion behavior in organic solvent-based electrolytes poses significant challenges in understanding charge transport mechanisms [6].

Ionic conductivity, influenced by solvent, salt, and additive selection, is key to optimizing ion transport. Organic solvents are commonly used due to their efficacy in dissolving lithium salts, which enhances ionic conductivity. This solvation capability fosters ion complex formation, significantly impacting charge transport mechanisms. The balance between solvent choice, lithium salt concentration, and additives is critical for optimizing the electrochemical performance and stability of lithium-ion and lithium-metal batteries. Recent advancements have explored various solvent combinations and concentrations to enhance energy density and operational efficiency, particularly under low-temperature conditions [8, 6, 9, 7]. However, the interactions between solvents and lithium ions, alongside solvation shell formation, complicate the modeling and optimization of charge transport properties.

The electrolyte composition also influences the formation of the solid electrolyte interphase (SEI) on the anode, which is crucial for battery efficiency and longevity. A well-formed SEI enhances ion transport by providing a stable interface for lithium ions, while a poorly formed SEI can impede flow and degrade performance. Understanding molecular interactions within electrolyte solutions is vital for creating advanced electrolytes that enhance lithium-ion battery efficiency. This involves analyzing the interplay between ion complexes, solvent interactions, and electrolyte component concentrations, all of which influence charge transport mechanisms and overall battery performance. Recent studies emphasize the importance of tailored compositions and the exploration of high-concentration electrolyte formulations to optimize properties and improve energy density and electrochemical stability in next-generation lithium-based energy storage systems [6, 9, 7].

1.3 Impact on Battery Performance and Safety

Electrolyte formulation is pivotal in determining lithium-ion battery performance metrics, including energy density, power output, cycling stability, and safety factors such as thermal stability and flammability. The composition of electrolytes directly influences the electrochemical stability window, ionic conductivity, and viscosity, which are critical for optimizing efficiency and safety. For instance, co-solvent electrolytes can extend the electrochemical stability window and enhance ionic conductivity, resulting in lithium batteries with superior specific energy and power metrics [8].

Temperature stability is a significant concern, as electrolyte degradation at elevated temperatures can lead to rapid capacity fade and increased resistance, affecting both lithium-ion and sodium-ion batteries. This thermal instability necessitates electrolyte formulations that maintain integrity under high-temperature conditions. Additionally, the flammability of conventional solvents poses safety risks, prompting the need for non-flammable alternatives, which may exhibit instability with lithium metal anodes [10].

Dendrite formation during cycling presents another safety hazard, potentially causing short circuits and battery failure. This issue is particularly severe in lithium metal batteries, where the instability of lithium metal anodes paired with Ni-rich layered cathodes compromises performance and safety [11]. Volume fluctuations during lithium metal cycling exacerbate these challenges by leading to SEI layer cracking, resulting in lithium corrosion and reduced battery life [12].

Innovations such as gel polymer electrolytes (GPEs) aim to address these issues by enhancing cycling stability and safety, mitigating dendritic growth, and preventing electrolyte leakage [13]. Furthermore, the coordination of anions with lithium ions, influenced by salt concentration, is crucial in forming a three-dimensional solution structure characteristic of high-concentration electrolytes, which can improve ionic mobility and stability [9].

Addressing these multifaceted challenges is essential for advancing lithium-ion battery technologies. This involves developing materials that offer high energy storage density, rapid reaction kinetics, and long-term stability while ensuring low toxicity and cost-effectiveness [14]. Overcoming these obstacles is critical for the safe and efficient deployment of lithium-ion batteries across various applications [15].

1.4 Structure of the Survey

This survey provides a comprehensive examination of battery electrolyte formulation in lithium-ion batteries, emphasizing its critical role in enhancing performance, efficiency, safety, and longevity. It begins with an introduction that highlights the significance of electrolyte formulation, detailing its role in ion transport and its impact on battery performance and safety. Following this, a detailed background on lithium-ion battery technology is presented, including definitions of key terms, a historical overview of electrolyte formulations, and a comparative analysis with other battery technologies.

Subsequent sections explore specific components and formulations of electrolytes, examining chemical constituents such as solvents, salts, and additives, and their roles in optimizing performance. The influence of electrolyte formulation on battery performance is analyzed, focusing on temperature effects and insights from empirical and theoretical studies. Safety and longevity considerations are addressed by identifying primary safety challenges and exploring strategies for enhancing safety and extending battery lifespan.

The survey also reviews recent advances and future directions in electrolyte formulation, highlighting innovations in materials and emerging trends in optimization. The conclusion synthesizes key findings from recent research on electrolyte formulations, emphasizing their role in improving lithium-ion battery performance and safety. It calls for exploration of alternative compositions, such as highly concentrated solutions and innovative additives, to tackle challenges like low-temperature performance and energy density optimization. Additionally, it suggests promising areas for future research, including molecular interactions within multicomponent electrolytes and the design of new

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additives to enhance charge transport and stability across various operating conditions [4, 6, 5, 7].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Overview of Lithium-Ion Battery Technology

Lithium-ion batteries (LIBs) are crucial in contemporary energy storage due to their high energy density, lightweight nature, and extended cycle life. Their architecture includes a cathode, an anode, an electrolyte, and a separator, with operation based on lithium ion intercalation between electrodes during charge and discharge cycles. The electrolyte facilitates lithium ion transport, converting chemical energy into electrical energy [15]. Typically, LIB electrolytes consist of lithium salts dissolved in organic solvents, offering high ionic conductivity but posing flammability risks [12]. This has driven research towards non-flammable, thermally stable formulations [16], while stability of single-atom catalysts enhances performance [17].

Recent advances include composite electrolytes with additives to stabilize the solid electrolyte interphase (SEI), crucial for anode protection and efficiency at high temperatures [18]. SEI acts as a barrier, preventing decomposition while allowing ion transport. Novel formulations also aim to enhance compatibility with high-energy-density materials, such as $LiNi_{0.5}Mn_{1.5}O_4$ cathodes and TiO_2 anodes, improving full cell performance [19]. Additionally, aqueous electrolytes with optimized salt concentrations show promise in stabilizing electrochemical processes in alternative batteries like zinc and sodium metal systems.

The evolution of LIB technology underscores the importance of electrolyte formulation for performance and safety optimization. Although traditional non-aqueous electrolytes have remained stable since the 1990s, exploring alternative formulations, including highly concentrated solutions, is crucial for enhancing energy storage capacity under varying conditions, such as low temperatures [4, 5, 7]. By refining electrolyte chemistry, researchers aim to support LIB applications in electronics and electric vehicles, emphasizing efficient ion transport and stability.

2.2 Key Definitions and Concepts

Understanding the complexities of electrolyte formulation in lithium-ion batteries involves concepts like electrolyte concentration, ion complex interactions, and the effects of additives and solvents on charge transport. Recent studies highlight the need to optimize these formulations to enhance energy density and operational efficiency under diverse temperature conditions, emphasizing the crucial role of electrolyte chemistry in advancing electrochemical storage systems [4, 6, 7].

Battery Electrolyte Formulation refers to the specific chemical combination within a LIB's electrolyte, significantly impacting ionic conductivity, stability, and performance. The electrolyte enables ion transport between electrodes, affecting aspects like charge-transfer kinetics, bulk transport properties, cycling stability, and SEI formation. The solvation energy of Li+ and the electrolyte's composition, including solvents, salts, and additives, can greatly influence efficiency, fast charging, and lifespan, underscoring the need for optimized formulations [19, 6, 16, 20, 7].

Electrolyte Composition involves the chemical formulation of the electrolyte, including solvents, lithium salts, and additives. Standard electrolytes typically use a 1 M solution of lithium hexafluorophosphate (LiPF6) in carbonate solvents. Advances have explored highly concentrated solutions to enhance performance by optimizing ion transport and energy density. Additives tailor properties to meet specific performance and safety needs in LIBs and lithium metal batteries [6, 9, 7]. Each component plays a role: solvents dissolve salts for ion transport, salts like $LiPF_6$ provide conduction ions, and additives improve stability and performance by modifying interactions with electrodes and SEI formation.

Battery Performance includes metrics like energy density, power output, cycle life, and thermal stability, all influenced by electrolyte formulation. High energy density is crucial for compact batteries, while power output is essential for rapid energy discharge. Cycle life measures the number of charge-discharge cycles before capacity degradation, and thermal stability prevents overheating and thermal runaway. Optimizing these metrics is vital for advancing energy storage, especially for continuous electricity generation from concentrated solar power systems [14].

A comprehensive understanding of LIB electrolyte definitions and concepts is foundational for advancing battery technology. This knowledge fosters innovative formulations that enhance performance metrics like efficiency, safety, and longevity. Recent research emphasizes optimizing composition—exploring highly concentrated solutions and incorporating additives—to improve energy density and performance, particularly under challenging conditions like low temperatures. By addressing complex interactions within solutions, researchers can design tailored formulations improving charge transport, reducing capacity loss, and enhancing reliability [4, 6, 5, 7].

2.3 Historical Development of Electrolyte Formulations

The evolution of electrolyte formulations in lithium-ion batteries has aimed at enhancing energy density, safety, and performance. Early developments used organic solvents and lithium salts, establishing high ionic conductivity but posing thermal stability and flammability challenges. As demand for higher energy densities grew, research shifted to alternative systems, such as those in Li-air and Li-oxygen batteries, which offer substantial energy potential but face electrolyte limitations [20].

The exploration of highly concentrated solutions has gained momentum, providing a promising avenue for improving ionic mobility and stability, addressing traditional low-concentration electrolyte limitations [7]. However, comprehensive analyses of key performance parameters in lithium-sulfur (Li–S) batteries, where energy density is critical, remain necessary [21].

The development of rechargeable alkaline zinc-air batteries (ZAB) illustrates historical progression. Efforts to enhance secondary zinc anodes focus on reducing corrosion and dissolution, significant commercialization challenges [22]. This has led to advanced formulations to improve ZAB efficiency.

Categorizing research by electrolyte types and degradation mechanisms has offered insights into additive roles in enhancing performance. Understanding molecular interactions in multicomponent solutions, particularly anion behavior, is critical. These insights inform stable and efficient electrolyte system design, although unstable solvents in localized high-concentration electrolytes continue to challenge [18].

Efforts to address low-temperature performance issues have influenced historical development. Since 2010, progress in electrolyte-based strategies has improved LIB performance under such conditions, reflecting ongoing innovation [4]. As research advances, optimizing formulations to meet increasing demand for safe, efficient, and high-performance energy storage remains a focus.

2.4 Comparative Analysis with Other Battery Technologies

Lithium-ion battery (LIB) electrolytes differ from those in other technologies, such as sodium-ion (SIBs) and magnesium/sulfur (Mg/S) batteries, due to specific requirements for high energy density, ionic conductivity, and safety. While LIBs use organic solvents and lithium salts for high ionic conductivity, they face flammability and thermal stability challenges. SIBs, with larger sodium ions, face slower ion diffusion and potential anode material damage [23], necessitating novel electrolyte systems accommodating larger ionic radii without compromising integrity.

Similarly, Mg/S battery advancement is constrained by the need for non-corrosive, efficient electrolytes, addressing common formulation issues [24]. The search for such electrolytes remains critical in advancing Mg/S technology. Solid-state electrolytes and high-nickel cathodes in LIBs represent significant innovations, enhancing safety and performance by eliminating flammable components [15].

Comparative analysis highlights diverse challenges and innovations across systems. Each technology requires unique formulations driven by specific ion properties. As research progresses, creating specialized systems tailored to different chemistries—such as highly concentrated solutions for LIBs and novel formulations for SIBs—will address performance limitations and facilitate significant energy storage innovations. This approach is essential for improving energy density, specific capacity, and overall efficiency and reliability under diverse conditions, including low and high temperatures [15, 25, 7, 5, 4].

3 Electrolyte Composition and Formulation

3.1 Chemical Components of Electrolytes

The chemical composition of lithium-ion battery electrolytes, comprising solvents, salts, and additives, is pivotal for performance, stability, and safety. Solvents, typically organic, dissolve lithium salts and serve as the medium for ionic conduction, influencing ionic conductivity and viscosity. The choice of solvents, such as 2,5-diamino-1,4-benzoquinone (DABQ), is crucial for enhancing stability and conductivity [2]. Lithium salts like lithium hexafluorophosphate ($LiPF_6$) provide conduction ions, with advances in solvent-in-salt systems broadening stability and transport properties. Localized high concentration electrolytes (LHCEs) maintain high salt concentrations with diluents, enhancing stability and conductivity [3].

Additives modify interactions with electrodes, improve solid electrolyte interphase (SEI) formation, and enhance safety. Additives like fluoroethylene carbonate (FEC) and tris(trimethylsilyl)phosphite (TMSPi) optimize low-temperature performance. Novel approaches, such as using aqueous $ZnCl_2NH_4Cl$, stabilize pH and control discharge product precipitation, offering alternatives to traditional alkaline electrolytes [3]. The integration of these components is essential for developing electrolytes that meet the demands of modern lithium-ion applications, focusing on high energy density, safety, and long-term stability. Recent research emphasizes non-standard formulations, including highly concentrated solutions, to optimize electrochemical performance by refining physicochemical properties and interactions [4, 5, 9, 7].

3.2 Role of Solvents in Electrolyte Formulation

Solvent selection in lithium-ion battery electrolytes is crucial for performance and stability. Solvents dissolve lithium salts, facilitating ion transport and influencing ionic conductivity, charge-transfer kinetics, and SEI stability [12, 19, 6, 20, 7]. Their physicochemical properties, such as dielectric constant and viscosity, affect conductivity, stability, and safety. Recent developments focus on non-flammable solvents to enhance safety, like hydrofluorocarbons mixed with lithium-coordinating ethers, balancing flammability risks and conductivity [10]. Localized high concentration electrolytes (LHCEs) optimize lithium-ion interactions and stability through strategic selection of salts, solvents, and diluents [9].

Solvents also influence interactions with electrodes, as seen in zinc-air batteries where specific formulations reduce corrosion and dissolution rates [22]. The careful formulation of solvents is vital for developing advanced electrolytes, achieving high conductivity, stability, and safety by optimizing interactions in multicomponent solutions [4, 6, 5, 7].

3.3 Additives and Their Impact

Additives enhance lithium-ion battery electrolyte performance and safety by modifying interactions with battery components. They improve SEI formation and stability, crucial for maintaining structural integrity and performance. Additives like tetraethoxysilane (TEOS) and (2-Cyanoethyl)triethoxysilane (TEOSCN) enhance SEI robustness on silicon anodes [26]. These additives improve cycling performance by stabilizing the SEI, reducing degradation over time [27].

Innovative strategies using hydrogen bonding create stable molecular crystal structures, maintaining low solubility and enhancing cycling stability [2]. The strategic selection of additives is crucial for improving safety and efficiency by optimizing SEI properties, thermal stability, and electrochemical performance. Functional additives, such as nitrile-functionalized silanes, significantly influence SEI composition, enhancing capacity retention and reducing safety risks. The exploration of highly concentrated solutions further improves performance, emphasizing the need for ongoing innovation in electrolyte chemistry to align with electrode advancements [26, 7].

Figure 2 illustrates the impact of various additives on lithium-ion battery performance, focusing on SEI enhancement, innovative strategies, and the role of concentrated solutions. This visual representation reinforces the discussion by providing a clear overview of how different additives contribute to the overall efficacy of lithium-ion batteries, thereby enhancing our understanding of their critical role in advancing battery technology.

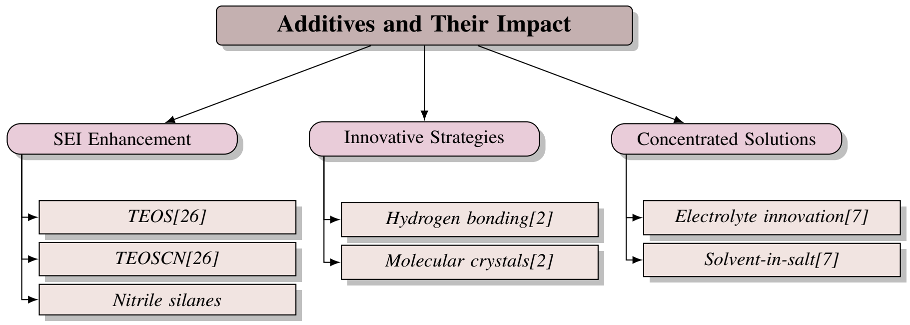

Figure 2: This figure illustrates the impact of various additives on lithium-ion battery performance, focusing on SEI enhancement, innovative strategies, and the role of concentrated solutions.

3.4 Ionic Conductivity and Stability

Ionic conductivity and stability are critical for lithium-ion battery performance and safety, influenced by electrolyte composition, including salts, solvents, and additives. For example, Mg_3Bi_2 with $Mg(TFSI)_2$/DME electrolyte optimizes conductivity [24]. Self-forming composite electrolytes enhance conductivity and stability, achieving 3.4 mS cm^{-1} at 25 °C [25]. Solvation energy, affected by concentration and anions, impacts conductivity and stability, providing insights for optimization [19].

A stable SEI reduces resistance, especially at low temperatures, achieved through careful formulation to protect the anode and allow efficient ion transport [16]. Maintaining SEI stability at varying temperatures is vital for longevity and safety.

In recent years, understanding the various factors that influence battery performance has become increasingly critical, particularly as the demand for more efficient energy storage solutions rises. A comprehensive analysis reveals that temperature and electrolyte performance play pivotal roles in determining overall battery efficacy. Figure 3 illustrates the hierarchical structure of these factors, emphasizing the interplay between temperature effects and electrolyte performance. This figure not only highlights empirical and theoretical insights into electrolyte composition but also underscores its significant impact on both efficiency and stability, thereby providing a visual representation that complements the discussion of these complex interactions within the text.

4 Influence on Battery Performance

4.1 Temperature Effects and Electrolyte Performance

Temperature fluctuations significantly impact lithium-ion battery electrolytes, affecting efficiency and safety. High temperatures can trigger electrolyte decomposition, reducing ionic conductivity and accelerating capacity loss. Asymmetric electrolytes have been shown to enhance cycling stability and performance of micro-sized alloying anodes under thermal stress, highlighting the importance of electrolyte design for high-temperature resilience [28, 5]. Conversely, low temperatures increase viscosity, hindering ionic mobility and conductivity. Binary-solvent electrolytes in Na||Na coin cells maintain performance from -20 °C to -80 °C, extending operational ranges in cold environments [16].

This is illustrated in Figure 4, which categorizes the effects of temperature on electrolyte performance into high and low temperature impacts, while also highlighting innovative strategies for enhancing electrolyte stability and performance under varying thermal conditions. Gel polymer electrolytes (GPEs) address temperature-related challenges by improving cycling stability and safety, suppressing dendritic growth, and enhancing thermal stability [13]. Additionally, non-concentrated aqueous electrolytes with DMC additives improve Zn anodes' electrochemical performance, achieving dendrite-free cycling over 1000 cycles with an average Coulombic efficiency of 99.8% [29]. In magnesium/sulfur battery systems, non-corrosive electrolytes reduce overpotential and improve cycling stability, demonstrating the effectiveness of tailored formulations in mitigating temperature-induced degradation [24]. Strategies to minimize corrosion and dendrite formation further enhance zinc anodes' electrochemical stability, contributing to overall performance improvements [22].

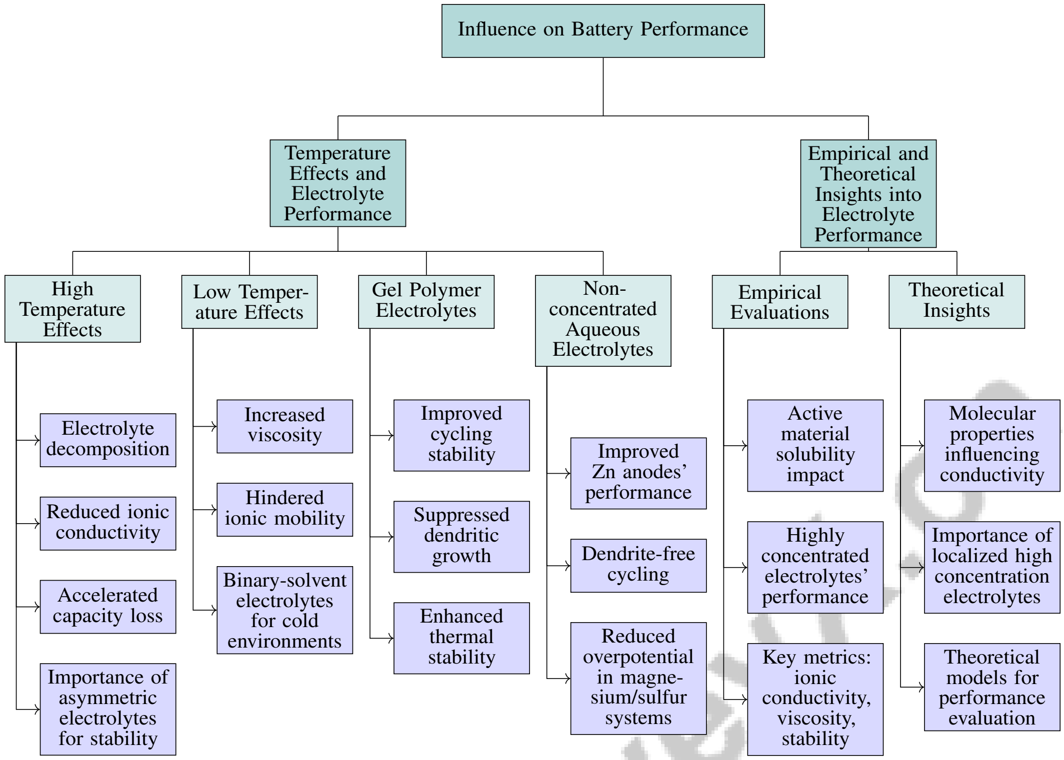

Figure 3: This figure illustrates the hierarchical structure of factors influencing battery performance, focusing on temperature effects and electrolyte performance, as well as empirical and theoretical insights into electrolyte composition and its impact on efficiency and stability.

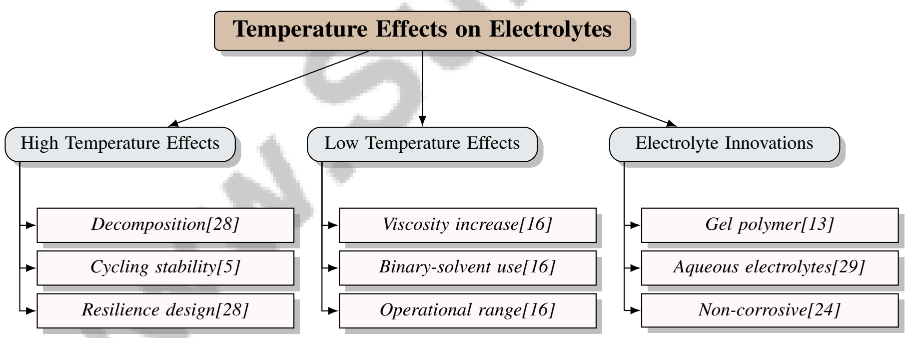

Figure 4: This figure illustrates the impact of temperature on electrolyte performance, categorizing the effects into high and low temperature impacts, and highlighting innovative strategies for enhancing electrolyte stability and performance under varying thermal conditions.

4.2 Empirical and Theoretical Insights into Electrolyte Performance

Empirical and theoretical evaluations of lithium-ion battery electrolytes reveal how composition affects efficiency and stability. Empirical studies on active material solubility, such as 2,5-diamino-1,4-benzoquinone (DABQ), link solubility to cycling stability and efficiency, underscoring its role in long-term performance [2]. Highly concentrated electrolytes, despite lower bulk conductivity, exhibit superior electrochemical performance, suggesting that stable ion complex formation is crucial for efficiency beyond ionic conductivity [7]. Key performance metrics, including ionic conductivity, viscosity, electrochemical stability window, and cycling stability, are extensively measured, providing insights into formulation effectiveness [8].

Theoretical insights complement empirical findings by elucidating complex interactions within electrolyte systems. Molecular properties significantly influence ionic conductivity, challenging simplistic mean-field approaches [6]. These insights are vital for developing efficient formulations that enhance lithium-ion transport and Coulombic efficiency, as demonstrated by localized high concentration electrolytes (LHCEs) [9]. Theoretical models also correlate cell potentials with Coulombic efficiency, offering frameworks for evaluating performance and guiding optimized formulation development [19]. Integrating empirical data and theoretical models is crucial for advancing electrolyte performance understanding, facilitating the development of formulations that enhance battery efficiency, stability, and longevity across various applications.

5 Safety and Longevity Considerations

Understanding and addressing the safety and longevity challenges in lithium-ion batteries require a detailed analysis of electrolyte formulations. This involves examining the interactions within electrolyte solutions and how variations in concentration and composition influence battery performance. By exploring these relationships, innovative strategies can be developed to enhance battery safety and reliability across diverse conditions [4, 7].

5.1 Safety Challenges in Electrolyte Formulations

The safety of lithium-ion batteries is intrinsically linked to electrolyte formulation, presenting challenges that must be resolved to ensure reliable operation. The formation and stability of the solid electrolyte interphase (SEI) are critical for performance, yet its degradation can lead to capacity loss and safety risks, particularly in silicon anodes where a stable SEI is beneficial [26]. Reactivity issues between conventional carbonate-based electrolytes and nickel-rich cathodes or lithium metal anodes exacerbate safety concerns, reducing Coulombic efficiency and increasing thermal runaway risks [11].

In zinc-air batteries, traditional alkaline electrolytes create corrosive environments that degrade zinc anodes, posing significant safety issues. pH instability during charging can lead to catalyst degradation, highlighting the need for stable electrolytes [3]. Additionally, high-temperature synthesis can cause atom agglomeration, leading to safety hazards like gas generation and accelerated aging.

Ionic liquids offer potential safety improvements due to their non-flammable nature, enhancing energy density and rate capability [30]. However, challenges include increased resistance at low temperatures and SEIs formed at ambient temperatures failing to protect in colder conditions. Reducing solubility without compromising gravimetric capacity or synthesis complexity remains critical [2]. Advanced electrolyte designs integrating experimental validation with computational predictions are essential for improving lithium-ion battery safety and reliability.

5.2 Strategies for Enhancing Safety

Enhancing the safety of lithium-ion battery electrolytes involves innovative design strategies to mitigate risks associated with thermal instability, flammability, and component degradation. The use of ionic liquids is promising due to their non-flammable properties and ability to modify interfaces, contributing to the safety and longevity of solid-state battery systems [25]. These ionic liquids help develop a stable SEI, crucial for battery integrity under various conditions.

Optimizing electrolyte formulations through rapid characterization methods allows precise adjustments to improve performance metrics like cyclability and rate capability [19]. Such techniques are crucial in developing safer lithium-ion batteries.

As illustrated in Figure 5, the strategies for enhancing safety in lithium-ion battery electrolytes focus on the integration of ionic liquids, optimized electrolyte formulations, and advanced materials. These elements collectively work to mitigate risks and extend battery lifespan. The dual-ion battery approach improves safety by enhancing cyclability and SEI stability, addressing degradation while ensuring long-term safety [12]. This exemplifies how innovative electrolyte designs can tackle safety challenges while maintaining high performance.

These strategies underscore the importance of integrating advanced materials and characterization techniques to develop safer lithium-ion battery electrolytes. Prioritizing stability and compatibility of components effectively mitigates safety risks and extends battery lifespan, particularly in electric vehicles and portable electronics. This approach addresses temperature fluctuations and electrolyte instability, leveraging advancements in formulations, including specific additives and solvent combinations, to optimize performance. These developments could accelerate the adoption of next-generation battery technologies, such as sodium-ion batteries, promising improved thermal stability and efficiency across varying temperatures [15, 16, 7, 5, 4].

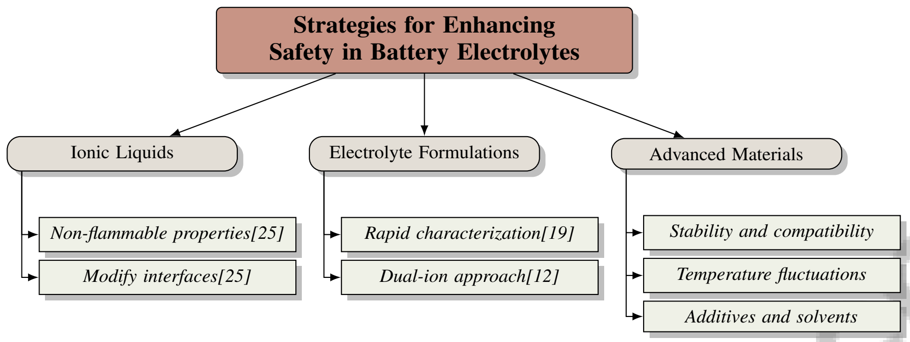

Figure 5: This figure illustrates the strategies for enhancing safety in lithium-ion battery electrolytes, focusing on ionic liquids, electrolyte formulations, and advanced materials to mitigate risks and extend battery lifespan.

5.3 Electrolyte Design for Longevity

Designing electrolytes is pivotal for enhancing the operational lifespan of lithium-ion batteries, significantly affecting stability, efficiency, and resistance to degradation. Recent research emphasizes optimizing electrolyte composition through concentration adjustments and specific additives, improving ionic conductivity and supporting stable SEI formation at electrode surfaces. This focus on electrolyte engineering addresses challenges like low-temperature performance and high-temperature cycling stability, facilitating the development of efficient energy storage systems [4, 5, 27, 7].

A key aspect of electrolyte design for longevity is establishing stable interfaces between the electrolyte and battery electrodes, particularly the SEI, which prevents continuous electrolyte decomposition and maintains electrode integrity. Future research should prioritize formulating stable electrolytes and lithium metal anodes, as these are critical for improving cycle life and battery performance [21]. The robustness of the SEI is vital, acting as a protective barrier against side reactions and mechanical degradation during repeated charge-discharge cycles, thereby reducing capacity fade and extending lifespan.

Advanced electrolyte formulations that incorporate additives to stabilize the SEI and suppress dendritic growth on lithium metal anodes are of particular interest. These additives enhance SEI uniformity and adhesion, improving protective capabilities and reducing short circuit risks from dendrite penetration. High-concentration electrolytes show promise in enhancing stable ion complex formation and bolstering SEI mechanical stability, crucial for extending sodium-ion battery cycle life, especially in high-temperature environments. Recent advancements in formulations, including synergistic additives like vinylene carbonate and sodium difluoro(oxalate)borate, have demonstrated effective NaF coatings and elastomeric layers that contribute to robust SEIs at both electrodes. These innovations address electrolyte instability challenges and pave the way for more efficient and durable sodium-ion battery technologies [7, 5].

Investigating solid-state electrolytes offers significant advantages in stability and safety compared to conventional liquid electrolytes. Solid-state systems enhance performance in extreme conditions, mitigating electrolyte resistance and SEI instability common in liquid systems. This exploration is increasingly relevant as the demand for reliable energy storage solutions grows across applications, from portable electronics to electric vehicles [19, 5, 16, 4]. Solid-state electrolytes could eliminate liquid electrolyte leakage and flammability issues, thereby improving the longevity and safety of lithium-ion batteries.

Strategically designing and optimizing electrolytes is crucial for enhancing the operational lifespan of lithium-ion batteries by improving electrochemical performance, particularly through advanced formulations that address ionic conductivity, temperature stability, and compatibility with electrode materials. Recent research highlights the potential of highly concentrated electrolyte solutions and tailored additives to significantly boost energy storage capabilities and mitigate capacity loss under challenging conditions, such as low temperatures or prolonged cycling [4, 5, 18, 7]. Focusing on stable interfaces, advanced additive formulations, and innovative electrolyte systems empowers researchers to develop batteries that perform efficiently while maintaining capacity and safety over extended use.

6 Recent Advances and Future Directions

6.1 Advancements in Electrolyte Materials

Recent progress in electrolyte materials for lithium-ion batteries has notably improved interfacial stability, safety, and performance across various conditions. Localized high concentration electrolytes (LHCEs) exemplify this advancement by balancing high ionic conductivity with reduced viscosity, enhancing lithium-ion transport and stability [9]. Asymmetric electrolytes have also significantly boosted cycling performance and electrode stability, reducing dendrite formation and structural degradation, which is vital for extending battery lifespan in demanding applications [11].

Figure 6 illustrates these advancements in electrolyte materials, highlighting the development of localized high concentration electrolytes, asymmetric electrolytes, and non-flammable gel polymer electrolytes, each contributing to improved stability, performance, and safety in lithium-ion battery applications. In high-energy-density scenarios, such as lithium-sulfur (Li–S) batteries, optimizing sulfur loading and electrode capacity ratios has been crucial for achieving desired performance metrics. The Mg_3Bi_2/S battery system, with its simple electrolyte formulation and minimized corrosion, showcases promising cycling performance and energy density [24]. Non-flammable gel polymer electrolytes that encapsulate liquid electrolytes represent a significant safety innovation, reducing flammability risks while maintaining high ionic conductivity [13]. Optimizing electrolyte additives has further improved the performance and safety of silicon anodes, essential for next-generation batteries [26].

Solid-state batteries are gaining attention for their potential to enhance safety and performance, potentially transforming electric vehicle technology [15]. Advances in synthesizing stable catalysts through high-temperature shockwave methods may also impact future electrolyte design [17]. Near-neutral $ZnCl_2NH_4Cl$ electrolytes, known for resisting carbonation and stabilizing pH, offer a novel design approach that enhances stability and performance [3]. These advancements highlight ongoing efforts to enhance the performance, safety, and sustainability of lithium-ion batteries, paving the way for efficient and reliable energy storage solutions.

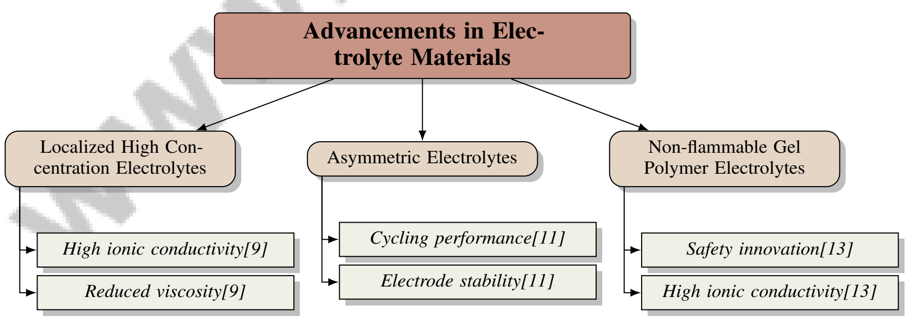

Figure 6: This figure illustrates the advancements in electrolyte materials, highlighting the development of localized high concentration electrolytes, asymmetric electrolytes, and non-flammable gel polymer electrolytes, each contributing to improved stability, performance, and safety in lithium-ion battery applications.

6.2 Future Research Directions in Electrolyte Design

Future research in electrolyte design should focus on optimizing molecular design, particularly organic compounds that benefit from hydrogen bond stabilization, to improve stability and performance [2]. Stabilizing pH during charging is crucial for enhancing the safety and efficiency of rechargeable zinc-air batteries, potentially leading to more reliable energy storage solutions [3]. Innovative formulations and additives that enhance thermal stability are essential for addressing degradation mechanisms, thereby improving the safety and longevity of lithium-ion batteries. Additives like vinylene carbonate and fluoroethylene carbonate have shown promise in modifying the solid electrolyte interphase (SEI) to enhance thermal stability and performance [4, 26, 7, 5].

Expanding design principles to create a broader range of solvent molecules and investigating alternative salts and solvents are crucial for optimizing low-temperature performance, extending operational ranges in cold environments. Prioritizing solid-state battery technologies and innovative recycling methods is essential for sustainable and cost-effective production, addressing the growing demand for reliable and environmentally friendly materials in the electric vehicle market [24, 15, 25, 21, 4]. Integrating multiple cation systems and interfacial engineering techniques will further boost battery performance and longevity. Addressing these research directions will enable advancements in safe, efficient, and high-performance lithium-ion battery technologies, meeting the increasing demands for advanced energy storage solutions.

6.3 Emerging Trends in Electrolyte Optimization

Recent advancements in electrolyte optimization for lithium-ion batteries focus on enhancing performance metrics like ionic conductivity, thermal stability, and safety. Localized high concentration electrolytes (LHCEs) effectively balance high ionic conductivity with reduced viscosity, improving lithium-ion transport and stability [9]. Asymmetric electrolytes have improved cycling performance and electrode stability, mitigating dendrite formation and structural degradation, thereby extending battery lifespan [11].

In high-energy-density applications like lithium-sulfur (Li–S) batteries, optimizing parameters such as sulfur loading and electrode capacity ratios is critical. The Mg_3Bi_2/S battery system exemplifies this trend with its straightforward electrolyte formulation and reduced corrosion issues [24]. Non-flammable gel polymer electrolytes that encapsulate liquid electrolytes enhance safety by reducing flammability risks while maintaining high ionic conductivity [13]. Optimizing electrolyte additives has improved silicon anode performance, which is vital for next-generation battery technologies [26].

Solid-state batteries promise higher safety and performance, with the potential to revolutionize electric vehicle technology [15]. Advances in synthesizing stable catalysts through high-temperature shockwave methods may influence future electrolyte design and optimization [17]. Near-neutral $ZnCl_2NH_4Cl$ electrolytes are noted for resisting carbonation and stabilizing pH, offering a novel approach to electrolyte design that enhances stability and performance [3]. These trends reflect ongoing efforts to improve the performance, safety, and sustainability of lithium-ion batteries, paving the way for more efficient and reliable energy storage solutions.

7 Conclusion

The survey underscores the pivotal role of electrolyte formulation in advancing lithium-ion battery performance and safety. The intricate balance of solvents, salts, and additives within electrolytes is crucial for optimizing ionic conductivity and electrochemical stability, thereby enhancing overall battery efficiency. Innovations such as localized high concentration electrolytes and gel polymer electrolytes offer promising solutions to mitigate flammability risks and improve ion transport. Addressing safety challenges, particularly thermal instability and dendrite formation, is vital for extending battery lifespan and ensuring reliability. The stability of the solid electrolyte interphase is essential in maintaining battery integrity, especially in high-energy-density applications. Future research should focus on refining molecular designs and exploring novel electrolyte formulations to enhance thermal stability and safety. The development of solid-state battery technologies and innovative recycling methods presents significant opportunities for sustainable battery production. Additionally, the integration of multiple cation systems and interfacial engineering can substantially boost battery performance and longevity.

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