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# 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 pivotal in determining the performance and safety of lithium-ion batteries, as it facilitates ion transport between the anode and cathode, directly impacting the cycle life and stability of the battery. The need for enhanced energy density and safety in rechargeable batteries is evident, as demonstrated by the challenges faced in the development of multivalent-ion batteries using water-based electrolytes [1]. Moreover, the formulation of electrolytes is crucial for improving battery performance under diverse conditions, such as low temperatures, where it plays a significant role in enhancing the performance of both lithium-ion and sodium metal batteries .

The high solubility of small organic materials in battery electrolytes presents challenges for maintaining gravimetric capacity, underscoring the importance of precise electrolyte formulation [2]. Additionally, the development of rechargeable zinc-air batteries (ZABs) highlights the necessity for innovative electrolyte formulations that can extend battery lifetime and performance, particularly through the use of near-neutral chloride electrolytes [3].

The formulation of electrolytes in lithium-ion batteries significantly impacts their operational efficiency, safety, and overall performance, while also addressing the stagnation in technological advancements observed since their commercialization in the early 1990s. Despite extensive research aimed at enhancing energy density through improvements in electrode materials, the electrolyte composition has remained largely unchanged, typically consisting of a one molar lithium hexafluorophosphate (LiPF<sub>6</sub>) solution in carbonate solvents. This lack of innovation in electrolyte chemistry

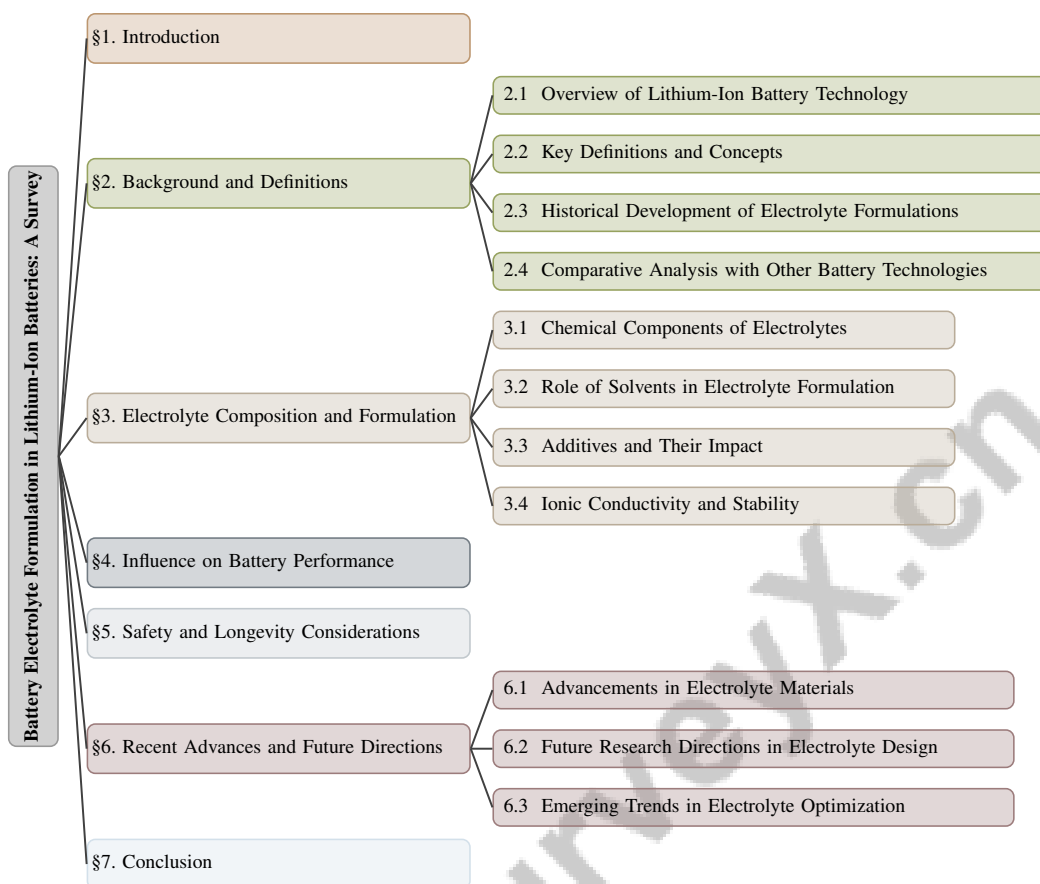


Figure 1: chapter structure

has prompted researchers to explore non-standard, highly concentrated electrolyte solutions and various additives, which have the potential to improve battery performance, particularly under challenging conditions such as low temperatures. Thus, advancing electrolyte formulation is crucial for overcoming current limitations and driving future developments in lithium-ion battery technology. [4, 5, 6]. Innovative approaches, such as the incorporation of composite electrolytes, are essential for enhancing power density, cycle life, and safety while ensuring environmental compatibility. These advancements are crucial for the development of high-energy density batteries that maintain performance and safety across various applications.

## 1.2 Role in Ion Transport

The role of electrolytes in facilitating ion transport is a fundamental aspect of lithium-ion battery functionality, as it directly affects both efficiency and overall performance. In lithium-ion batteries, the electrolyte serves as a medium for the movement of lithium ions between the anode and cathode during the charge and discharge cycles. This ion transport is essential for the conversion of chemical energy into electrical energy and vice versa. The complexity of ion behavior in organic solvent-based electrolyte solutions poses significant challenges, particularly in understanding the charge transport mechanisms [7].

The efficiency of ion transport is largely determined by the ionic conductivity of the electrolyte, which is influenced by the choice of solvents, salts, and additives. These components must be carefully selected to optimize the balance between ionic mobility and electrolyte stability. Organic solvents are often used due to their ability to dissolve lithium salts effectively, thus facilitating high ionic conductivity. The interaction between solvent molecules and lithium ions, along with the resulting formation of solvation shells, plays a crucial role in influencing the charge transport properties of electrolyte solutions in lithium-ion and lithium metal batteries. This complexity arises from the intricate relationships between ion-solvent and ion-ion interactions, which are essential for

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optimizing battery performance. Specifically, the choice of solvent and its ability to stabilize lithium ions through solvation directly affects charge-transfer kinetics, electrolyte bulk transport, and the stability of the solid-electrolyte interphase (SEI). Therefore, accurately modeling and optimizing these interactions is essential for enhancing the efficiency and longevity of modern electrochemical storage devices. [8, 9, 7, 10, 11]

The composition of the electrolyte, particularly its concentration and the inclusion of specific additives, significantly influences the formation and characteristics of the solid electrolyte interphase (SEI) on the anode surface. This SEI is essential for optimizing battery performance, as it affects not only the ionic conductivity and charge transfer kinetics but also the overall cycling stability, safety, and longevity of lithium-ion batteries. Recent studies indicate that tailored electrolyte formulations can lead to thinner and more stable SEI layers, enhancing the electrochemical efficiency and operational lifespan of batteries, especially those utilizing high-capacity anode materials like silicon. [12, 11, 6]. A well-formed SEI layer can enhance ion transport by providing a stable interface for lithium ion movement, while a poorly formed SEI can impede ion flow and degrade battery performance. Understanding these interactions at a molecular level is vital for the development of advanced electrolyte formulations that can improve the efficiency and functionality of lithium-ion batteries.

### 1.3 Impact on Battery Performance and Safety

The formulation of electrolytes in lithium-ion batteries is pivotal in determining their performance metrics, including energy density, power output, and cycling stability, alongside safety considerations such as thermal stability and flammability. Electrolyte composition directly affects the electrochemical stability window, ionic conductivity, and viscosity, which are critical for optimizing both efficiency and safety. For example, co-solvent electrolytes have been shown to extend the electrochemical stability window and enhance ionic conductivity, thereby enabling lithium batteries with superior specific energy and power metrics [13].

Temperature stability remains a significant concern, as electrolyte degradation at elevated temperatures can lead to rapid capacity fade and increased resistance, impacting both lithium-ion and Na-ion batteries. Such thermal instability underscores the necessity for electrolyte formulations that maintain integrity under high-temperature conditions. Moreover, the inherent flammability of conventional solvents presents safety risks, necessitating the development of non-flammable alternatives, although these often exhibit instability with Li-metal anodes [14].

Dendrite formation during cycling poses another safety hazard, as it can lead to short circuits and battery failure. This is particularly problematic in lithium metal batteries, where the instability of lithium metal anodes when paired with Ni-rich layered cathodes compromises performance and safety [15]. Volume fluctuations during Li metal cycling exacerbate the situation by causing SEI layer cracking, leading to lithium corrosion and reduced battery life [9].

Innovations such as gel polymer electrolytes (GPEs) have been proposed to address these issues by enhancing cycling stability and safety, mitigating dendritic growth, and preventing electrolyte leakage [16]. Additionally, the coordination behavior 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 [10].

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, all while ensuring low toxicity and cost-effectiveness [17]. Overcoming these obstacles is critical for the safe and efficient deployment of lithium-ion batteries across a range of applications [18].

### 1.4 Structure of the Survey

This survey is structured to provide a comprehensive examination of battery electrolyte formulation in lithium-ion batteries, highlighting its critical role in enhancing battery performance, efficiency, safety, and longevity. The survey begins with an introduction that underscores the significance of electrolyte formulation, elaborating on its pivotal role in ion transport and its impact on battery performance and safety. This section is followed by a detailed background on lithium-ion battery technology, which

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includes definitions of key terms and concepts, a historical overview of electrolyte formulations, and a comparative analysis with other battery technologies.

Subsequent sections delve into the specific components and formulation of electrolytes, examining the chemical constituents such as solvents, salts, and additives, and their respective roles in optimizing electrolyte performance. The influence of electrolyte formulation on battery performance is thoroughly analyzed, with a focus 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 provides a comprehensive analysis of recent advancements in electrolyte formulation for lithium-ion batteries, emphasizing key innovations in materials such as high-nickel cathodes and novel liquid and solid-state electrolytes. It also identifies emerging trends in electrolyte optimization, including the exploration of highly concentrated electrolyte solutions and the development of tailored additives to enhance performance, particularly in challenging conditions like low temperatures. These insights are crucial for understanding the future landscape of battery chemistries, especially in the context of electric vehicle applications. [4, 5, 18, 6]. The conclusion synthesizes the key findings and reflects on the importance of electrolyte formulation in optimizing lithium-ion battery performance and safety, while suggesting potential areas for future research and development. 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 integral to modern energy storage, known for their high energy density, lightweight nature, and long cycle life. A LIB consists of a cathode, anode, electrolyte, and separator, with lithium ions intercalating between electrodes during charge and discharge cycles, converting chemical to electrical energy [18]. Typically, LIB electrolytes comprise lithium salts in organic solvents, offering high ionic conductivity but presenting flammability risks [9]. Research aims to develop non-flammable, thermally stable electrolytes to mitigate these risks [19]. The stability of single-atom catalysts is also crucial for enhancing battery performance [20].

Recent advancements include composite electrolytes with additives to form stable solid electrolyte interphases (SEIs), protecting anodes and maintaining efficiency, particularly at high temperatures [21]. SEIs prevent electrolyte decomposition, allowing lithium ion transport and improving cycle life and safety. Innovations in electrolyte formulation, such as incorporating  $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$  cathodes and nanostructured  $\text{TiO}_2$  anodes, enhance compatibility with high-energy-density materials [11]. Aqueous electrolytes with optimized salt concentrations and additives stabilize electrochemical processes in zinc and sodium metal batteries.

The evolution of LIB technology highlights the importance of electrolyte formulation in achieving performance and safety standards. As demand for advanced energy storage grows, research focuses on electrolytes' role in ion transport and battery stability, particularly in lithium-ion and sodium-ion batteries. Non-standard formulations significantly impact energy density and cycling stability, with tailored additives in sodium-based electrolytes stabilizing SEIs and addressing temperature instability challenges [4, 6].

### 2.2 Key Definitions and Concepts

Understanding electrolyte formulation is essential in lithium-ion batteries, involving solvent composition, ion complex formation, and lithium salt concentration, which influence charge transport and performance. Since their commercialization in the early 1990s, standard formulations have largely persisted, but recent research emphasizes non-standard, highly concentrated solutions to enhance energy density and efficiency [7, 6].

**Battery Electrolyte Formulation** entails the chemical components in a LIB's electrolyte, crucial for ionic conductivity, stability, and performance. Research highlights electrolyte composition's role, including salt concentration and additives, in enhancing energy storage and stable operation under varied conditions. Highly concentrated solutions improve charge transport and SEI formation, boosting battery performance and longevity [4, 10, 7, 6].

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**Electrolyte Composition** involves solvents, salts, and additives. Solvents dissolve lithium salts, facilitating ion transport. Salts like  $\text{LiPF}_6$  provide necessary ions, while additives improve stability, safety, and performance by enhancing SEI formation and interaction dynamics. Additives such as tetraethoxysilane and fluoroethylene carbonate create stable SEIs, optimizing capacity and longevity by preventing dendritic growth [4, 15, 12, 6].

**Battery Performance** includes metrics like energy density, power output, cycle life, and thermal stability, directly influenced by electrolyte formulation. High energy density suits compact applications, while power output supports rapid discharge needs. Cycle life measures charge-discharge cycles before capacity degrades, and thermal stability ensures safety by preventing overheating. Optimizing these metrics is vital for reliable energy storage solutions, such as those in concentrated solar power systems [17].

Comprehending these definitions and concepts is vital for advancing battery technology. This knowledge enables innovative formulations that enhance performance metrics like energy efficiency, safety, and longevity. Recent studies emphasize electrolyte composition, such as lithium salt concentration and solvent choice, in optimizing charge transport and mitigating temperature-related issues. Insights from electrolyte engineering, including additives and non-standard solutions, expand lithium-ion batteries' functionality, addressing current challenges and future applications [7, 5, 4, 6].

### 2.3 Historical Development of Electrolyte Formulations

The evolution of electrolyte formulations in LIBs has focused on enhancing energy density, safety, and performance. Initial developments used organic solvents and lithium salts for high ionic conductivity but faced thermal stability and flammability challenges. As energy density demands increased, research explored alternative systems like Li-air and Li-oxygen batteries, offering potential but limited by suitable electrolytes [8].

Recently, highly concentrated electrolyte solutions have gained attention for improving energy storage performance in lithium-based batteries, enhancing ionic mobility and stability [6]. Despite advancements, comprehensive analyses of performance parameters, especially in lithium-sulfur batteries, remain needed [22]. The development of rechargeable alkaline zinc-air batteries (ZABs) highlights electrolyte formulation progression, focusing on reducing zinc corrosion and dissolution for commercialization [23].

Research categorizing electrolyte types and degradation mechanisms informs additive roles in enhancing performance. Understanding molecular interactions in multicomponent solutions, particularly anion behavior, remains critical, informing stable and efficient electrolyte design [21]. Despite unstable solvents in localized high-concentration electrolytes posing challenges, progress continues.

Efforts to address low-temperature performance issues since 2010 reflect ongoing evolution and innovation in electrolyte-based strategies for LIBs [5]. Optimizing formulations to meet demands for safe, efficient, high-performance energy storage solutions remains a research focus.

### 2.4 Comparative Analysis with Other Battery Technologies

LIB electrolytes differ from those in other technologies like sodium-ion (SIBs) and magnesium/sulfur (Mg/S) batteries, requiring high energy density, ionic conductivity, and safety. LIBs use organic solvents and lithium salts for conductivity but face flammability and thermal stability challenges. SIBs, with larger sodium ions, require novel electrolytes to prevent structural damage during cycles [24].

Mg/S batteries face challenges with corrosive and complex electrolytes, hindering advancement [25]. Non-corrosive, efficient electrolytes are critical for progress. Solid-state electrolytes and high-nickel cathodes in LIBs offer safety and performance improvements by removing flammable liquid components [18].

Comparing LIB electrolytes with those in other technologies reveals unique challenges and strategies for performance enhancement. Advancements in formulations, like concentrated solutions and novel additives, aim to improve performance and energy density. Addressing these challenges is critical for optimizing battery efficiency, safety, and longevity across diverse conditions [5, 18, 11, 6]. Tailored

electrolyte systems for each battery type are essential for overcoming limitations and achieving energy storage breakthroughs.

### 3 Electrolyte Composition and Formulation

The formulation of electrolytes is crucial for the performance and safety of lithium-ion batteries, requiring an understanding of the interactions between solvents, salts, and additives. This section examines the chemical components of electrolytes and their contributions to the system's functionality. Table 2 provides a comparative overview of the chemical components, roles of solvents, and the impact of additives in the formulation of electrolytes for lithium-ion batteries, emphasizing their contributions to performance and safety. Figure 2 illustrates the hierarchical structure of electrolyte composition and formulation in lithium-ion batteries, highlighting the various chemical components, the role of solvents, the impact of additives, and the factors affecting ionic conductivity and stability. By analyzing this figure, we can gain deeper insights into how these elements interact and influence the overall efficiency of the battery system.

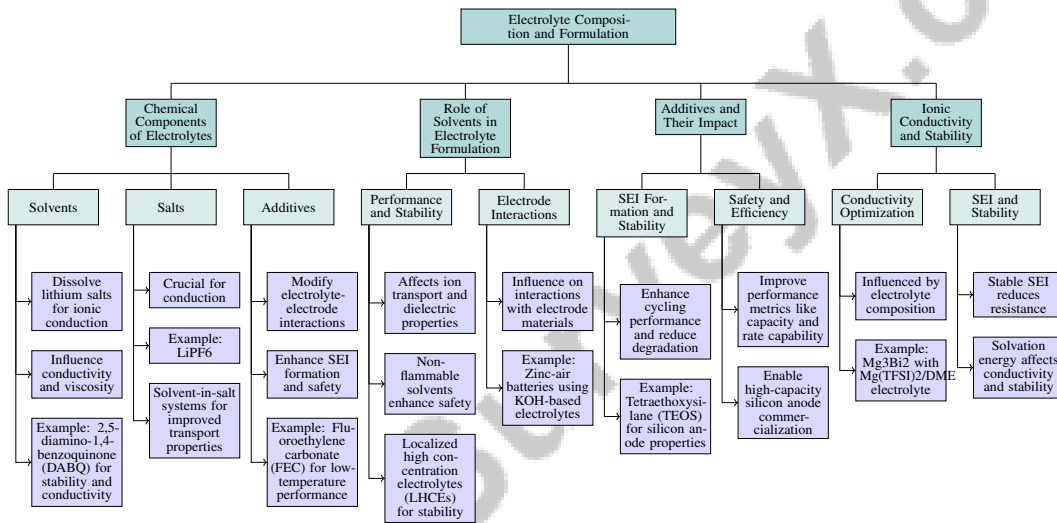


Figure 2: This figure illustrates the hierarchical structure of electrolyte composition and formulation in lithium-ion batteries, highlighting chemical components, the role of solvents, the impact of additives, and factors affecting ionic conductivity and stability.

#### 3.1 Chemical Components of Electrolytes

The electrolyte's chemical composition, comprising solvents, salts, and additives, is vital for lithium-ion battery performance, stability, and safety. As illustrated in Figure 3, this figure highlights the key chemical components of electrolytes in lithium-ion batteries, emphasizing the roles of organic solvents, lithium salts, and additives in enhancing performance, stability, and safety. Organic solvents dissolve lithium salts, facilitating ionic conduction and influencing properties like conductivity and viscosity. The molecular design of solvents, such as 2,5-diamino-1,4-benzoquinone (DABQ), enhances stability and ionic conductivity through hydrogen bonding [2]. Lithium salts, such as  $\text{LiPF}_6$ , are crucial for conduction, with solvent-in-salt systems offering improved transport properties [3]. Additives modify electrolyte-electrode interactions, enhance SEI formation, and improve safety, with examples like fluoroethylene carbonate (FEC) enhancing low-temperature performance [3]. The strategic integration of these components aims to achieve high energy density, safety, and stability, challenging traditional formulations since the 1990s [4, 6].

#### 3.2 Role of Solvents in Electrolyte Formulation

Solvent choice is pivotal in determining the electrolyte system's performance and stability. Solvents dissolve lithium salts, facilitating ion transport, with properties like dielectric constant and viscosity

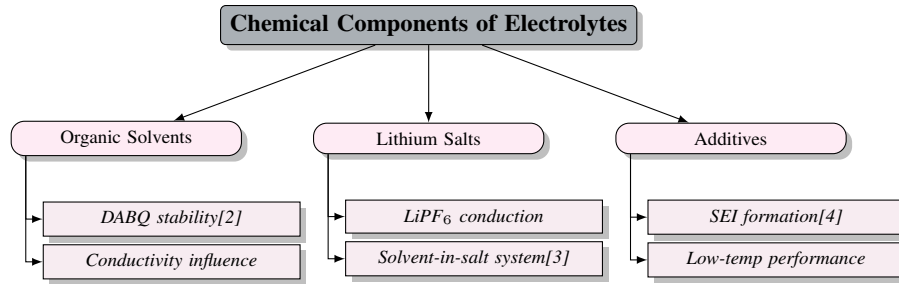


Figure 3: This figure illustrates the key chemical components of electrolytes in lithium-ion batteries, highlighting the roles of organic solvents, lithium salts, and additives in enhancing performance, stability, and safety.

affecting conductivity and stability [5, 7, 10, 11, 6]. Recent advancements focus on non-flammable solvents to enhance safety, such as hydrofluorocarbons and lithium-coordinating ethers [14]. Localized high concentration electrolytes (LHCEs) optimize lithium-ion interactions, enhancing stability and transport properties [10]. Solvents also influence interactions with electrode materials, as seen in zinc-air batteries using KOH-based electrolytes to reduce corrosion [23]. The careful formulation of solvents is essential for achieving a balance of conductivity, stability, and safety [4, 6, 7].

### 3.3 Additives and Their Impact

Additives enhance lithium-ion battery electrolytes by improving SEI formation and stability. Additives like tetraethoxysilane (TEOS) and (2-Cyanoethyl)triethoxysilane (TEOSCN) improve silicon anode properties [12]. They enhance cycling performance by stabilizing the SEI, reducing degradation [26]. Molecular design strategies, such as hydrogen bonding, maintain low solubility and improve cycling stability [2]. Additives are crucial for enhancing battery safety and efficiency, improving performance metrics like capacity and rate capability, and enabling high-capacity silicon anode commercialization [4, 12].

### 3.4 Ionic Conductivity and Stability

Method Name	Material Composition	Performance Metrics	Environmental Conditions
Mg3Bi2/S[25]	Mg(tfsi)2/dme	Cycling Performance	Current Densities
SFCE[27]	La3+ Ions	Ionic Conductivity	Temperature
PM[11]	Lithium Bis(fluorosulfonyl)imide	Coulombic Efficiency	Temperature And Solvation
BSEF[19]	Sodium Trifluoromethanesulfonate Salt	Cycling Stability	Below 0 °C

Table 1: Summary of various electrolyte compositions and their corresponding performance metrics and environmental conditions for lithium-ion battery applications. The table highlights the influence of different material compositions on cycling performance, ionic conductivity, coulombic efficiency, and stability under varying environmental conditions.

Ionic conductivity and stability are critical for lithium-ion battery performance. Electrolyte composition, including salts, solvents, and additives, determines these properties. Table 1 presents a comprehensive overview of different electrolyte compositions and their impact on key performance metrics and environmental conditions, which are crucial for enhancing the ionic conductivity and stability of lithium-ion batteries. For instance, Mg<sub>3</sub>Bi<sub>2</sub> with Mg(TFSI)<sub>2</sub>/DME electrolyte optimizes conductivity [25]. Composite electrolytes have shown significant conductivity improvements, achieving 3.4 mS cm<sup>-1</sup> at 25 °C [27]. Solvation energy, influenced by concentration and solvent interactions, affects conductivity and stability [11]. A stable SEI is essential for reducing resistance, especially at low temperatures, achieved through careful formulation [19]. Understanding these factors is vital for designing efficient, reliable lithium-ion batteries.

## 4 Influence on Battery Performance

The performance of lithium-ion batteries is intricately linked to electrolyte behavior under varying thermal conditions. This section investigates the temperature-dependent effects on electrolyte perfor-

Feature	Chemical Components of Electrolytes	Role of Solvents in Electrolyte Formulation	Additives and Their Impact
Key Component	Solvents, Salts, Additives	Non-flammable Solvents	Teos, Teoscn
Performance Enhancement	High Energy Density	Ion Transport Facilitation	Improved Cycling Stability
Safety Feature	Improved Sei Formation	Enhanced Stability	Enhanced Sei Formation

Table 2: This table presents a comparative analysis of the chemical components, solvent roles, and additive impacts in electrolyte formulations for lithium-ion batteries. It highlights the key components such as solvents, salts, and additives, and their contributions to performance enhancement and safety features, including high energy density, ion transport facilitation, and improved SEI formation. The data underscores the critical role these elements play in optimizing battery efficiency and stability.

mance, emphasizing the critical interactions that affect efficiency and stability. Understanding these dynamics is vital for optimizing battery formulations and ensuring reliable operation across diverse thermal environments.

#### 4.1 Temperature Effects and Electrolyte Performance

Temperature fluctuations significantly affect the performance and stability of lithium-ion battery electrolytes, impacting efficiency and safety. Elevated temperatures can accelerate electrolyte decomposition, affecting ionic conductivity and hastening capacity fade. Asymmetric electrolytes have been shown to enhance the cycling performance and stability of micro-sized alloying anodes, improving overall battery metrics under thermal stress [28, 4]. Conversely, low temperatures increase electrolyte viscosity, reducing ionic mobility and conductivity. Binary-solvent electrolytes in Na||Na coin cells have demonstrated performance retention at sub-zero temperatures from -20 °C to -80 °C, extending battery operability in cold environments [19]. Gel polymer electrolytes (GPEs) effectively address temperature-related issues by enhancing cycling stability and safety, suppressing dendritic growth, and improving thermal stability [16]. Non-concentrated aqueous electrolytes with DMC additives significantly enhance Zn anode electrochemical performance, achieving dendrite-free cycling over 1000 cycles with a high average Coulombic efficiency of 99.8

#### 4.2 Empirical and Theoretical Insights into Electrolyte Performance

Empirical and theoretical assessments of electrolyte performance provide a comprehensive understanding of the influence of electrolyte composition on battery efficiency and stability. Empirical studies highlight the correlation between the solubility of active materials, such as 2,5-diamino-1,4-benzoquinone (DABQ), and cycling stability and efficiency [2]. Highly concentrated electrolytes, despite lower bulk conductivity, can deliver superior electrochemical performance, indicating the importance of stable ion complex formation over mere ionic conductivity [6]. Key performance metrics such as ionic conductivity, viscosity, electrochemical stability window, and cycling stability have been extensively measured, offering insights into the effectiveness of various electrolyte formulations [13]. Theoretical insights complement empirical findings by elucidating complex interactions within electrolyte systems. Molecular properties significantly influence ionic conductivity, challenging simplistic mean-field approaches [7]. These insights are crucial for developing efficient electrolyte formulations that enhance lithium-ion transport and Coulombic efficiency, as demonstrated by localized high concentration electrolytes (LHCEs) [10]. Theoretical models have also established correlations between cell potentials and Coulombic efficiency, providing a framework for evaluating electrolyte performance and guiding optimized formulation development [11]. Integrating empirical data and theoretical models advances our understanding of electrolyte performance, enabling the development of formulations that enhance battery efficiency, stability, and longevity across diverse applications.

### 5 Safety and Longevity Considerations

Addressing the safety and longevity of lithium-ion batteries necessitates a comprehensive understanding of electrolyte formulations and their complex interactions. This section explores how concentration and composition affect ionic conductivity, solvation energy, and low-temperature performance, providing insights into mechanisms that influence battery efficiency and reliability. Such knowledge is essential for developing innovative strategies to enhance safety and performance, particularly as the demand for electric vehicles and portable electronics rises [5, 18, 11, 6].



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## 5.1 Safety Challenges in Electrolyte Formulations

The formulation of electrolytes is crucial to the safety of lithium-ion batteries, with significant challenges arising from the solid electrolyte interphase (SEI). The SEI's stability is vital for battery performance, yet its degradation can lead to capacity decay and safety risks, particularly in silicon anodes [12]. Conventional carbonate-based electrolytes exacerbate these issues due to their reactivity with nickel-rich cathodes and lithium metal anodes, increasing the risk of thermal runaway [15]. Alkaline electrolytes also pose safety risks by degrading zinc anodes in zinc-air batteries (ZABs), highlighting the need for stable formulations [3]. High-temperature synthesis of electrolytes can lead to atom agglomeration, gas generation, and accelerated aging. Ionic liquids offer a non-flammable alternative, enhancing energy density and rate capability [29], but challenges remain in maintaining SEI protection at low temperatures. The reduction of solubility without compromising performance or increasing synthesis complexity is ongoing [2]. Innovative designs and methodologies that integrate experimental and computational approaches are essential for advancing safety and reliability in lithium-ion batteries.

## 5.2 Strategies for Enhancing Safety

Enhancing the safety of lithium-ion battery electrolytes involves innovative strategies to mitigate risks of thermal instability, flammability, and component degradation. Ionic liquids, due to their non-flammable nature, improve interfacial modification and contribute to stable SEI formation, crucial for battery integrity [27]. Optimizing electrolyte formulations through rapid characterization methods allows precise adjustment of components, improving metrics like cyclability and rate capability [11]. Dual-ion batteries enhance safety by maintaining a stable SEI and improving rate capability [9]. These strategies underscore the need for advanced materials and characterization techniques in developing safer electrolytes. Recent studies emphasize the role of electrolyte composition—including additives, solvents, and lithium salts—in optimizing electrochemical performance and stability, highlighting the importance of innovative engineering in advancing lithium-ion technology [5, 10, 11].

## 5.3 Electrolyte Design for Longevity

Electrolyte design is pivotal for extending the lifespan of lithium-ion batteries by enhancing stability, efficiency, and resistance to degradation. A stable SEI between the electrolyte and electrodes minimizes decomposition and ensures structural integrity. Advanced formulations with specific additives have shown to form robust SEI layers, enhancing thermal stability and cycling performance across temperatures. For instance, sodium-ion batteries with novel formulations establish stable SEI at high temperatures, while tailored lithium-ion systems improve cycling stability and charge-transfer kinetics [4, 19, 12, 11, 6]. Future research should focus on stable electrolytes and lithium metal anodes to improve cycle life [22]. Additives that stabilize the SEI and suppress dendritic growth on lithium metal anodes are crucial, as high-concentration electrolytes facilitate robust ion complexes, extending cycle life, especially in sodium-ion technology [16, 4, 19, 10, 6]. Solid-state electrolytes offer stability and safety advantages over liquid systems, reducing degradation and capacity loss, essential for applications like electric vehicles and portable electronics [4, 5]. By focusing on stable interfaces, advanced additive formulations, and innovative systems, researchers can enhance efficiency, safety, and capacity retention. Recent advancements in sodium-ion battery electrolytes and highly concentrated solutions in lithium-ion batteries underscore the critical role of electrolyte engineering in maintaining functionality across conditions [4, 5, 18, 6].

# 6 Recent Advances and Future Directions

Advancements in electrolyte materials are pivotal for enhancing the performance and safety of lithium-ion batteries. This section delves into recent innovations in electrolyte formulations that improve interfacial stability and overall battery functionality, focusing on significant trends and future research directions.

## 6.1 Advancements in Electrolyte Materials

Recent developments in electrolyte materials have significantly improved the interfacial stability, safety, and performance of lithium-ion batteries across various conditions. Localized high concentra-

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tion electrolytes (LHCEs) are a notable innovation, offering a balance of high ionic conductivity and reduced viscosity, which enhances lithium-ion transport and stability [10]. Asymmetric electrolytes further improve cycling performance and electrode stability by mitigating dendrite formation and structural degradation [15], extending battery lifespan in demanding applications.

In high-energy-density contexts, such as lithium-sulfur (Li-S) batteries, optimizing sulfur loading and electrode capacity ratios is crucial. The  $\text{Mg}_3\text{Bi}_2/\text{S}$  battery system exemplifies this with its simple electrolyte formulation and reduced corrosion issues, demonstrating promising performance and energy density [25]. Additionally, non-flammable gel polymer electrolytes encapsulating liquid electrolytes enhance safety by reducing flammability risks while maintaining high ionic conductivity [16]. Electrolyte additives remain critical, with recent optimizations improving the performance and safety of silicon anodes, crucial for next-generation technologies [12].

Solid-state battery exploration promises higher safety and performance, potentially leading future electric vehicle technology [18]. Advances in synthesizing stable catalysts via high-temperature shockwave methods may influence future electrolyte design [20]. Near-neutral  $\text{ZnCl}_2\text{NH}_4\text{Cl}$  electrolytes offer a novel approach to resisting carbonation and stabilizing pH, enhancing stability and performance [3]. These advancements highlight ongoing efforts to improve lithium-ion battery performance, safety, and sustainability.

## 6.2 Future Research Directions in Electrolyte Design

Future electrolyte design research should focus on optimizing formulations to enhance battery performance across applications. Molecular design optimization, particularly exploring organic compounds stabilized by hydrogen bonds, could improve electrolyte stability and performance [2]. Stabilizing pH during charging is crucial for safer, more efficient rechargeable zinc-air batteries [3].

Research should prioritize innovative electrolytes and additives that enhance thermal stability and reduce degradation in lithium-ion batteries. Specific additives like vinylene carbonate and fluoroethylene carbonate contribute to robust SEI formation and thermal stability. Highly concentrated electrolyte solutions may optimize performance under various conditions, addressing capacity loss and safety during high-temperature cycling [4, 5, 26, 12, 6]. Expanding solvent molecule design principles could significantly enhance lithium metal battery performance, opening new avenues for innovation. Exploring alternative salts and solvents is essential for optimizing low-temperature performance, extending operational range in cold environments.

Solid-state battery technologies and innovative recycling methods should be prioritized for sustainable, cost-effective production. Integrating multiple cation systems and interfacial engineering can boost performance and longevity. Focusing on these research directions will advance lithium-ion battery technologies, meeting the demand for sophisticated energy storage solutions, particularly in the electric vehicle market. Innovations in electrode materials, such as high-nickel cathodes and silicon anodes, alongside advancements in electrolyte formulations, are expected to enhance capacity, reduce costs, and improve sustainability and recyclability, supporting the transition to renewable energy and electrification of transportation systems [29, 5, 18].

## 6.3 Emerging Trends in Electrolyte Optimization

Recent advancements in electrolyte optimization for lithium-ion batteries focus on enhancing ionic conductivity, thermal stability, and safety. Localized high concentration electrolytes (LHCEs) balance high ionic conductivity with reduced viscosity, improving lithium-ion transport and stability [10]. Asymmetric electrolytes improve cycling performance and electrode stability, mitigating dendrite formation and structural degradation, thus extending battery lifespan [15].

In high-energy-density applications like lithium-sulfur (Li-S) batteries, optimizing sulfur loading and electrode capacity ratios is a key focus. The  $\text{Mg}_3\text{Bi}_2/\text{S}$  battery system demonstrates this trend with its simple electrolyte formulation and reduced corrosion issues, showing promising performance and energy density [25]. Non-flammable gel polymer electrolytes enhance safety by mitigating flammability risks while maintaining high ionic conductivity [16]. Electrolyte additives remain crucial, with recent optimizations enhancing silicon anode performance and safety, vital for next-generation technologies [12].

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Solid-state batteries are gaining traction, promising higher safety and performance, potentially dominating future electric vehicle technology [18]. Advances in stable catalyst synthesis through high-temperature shockwave methods may influence future electrolyte design [20]. Near-neutral  $\text{ZnCl}_2\text{NH}_4\text{Cl}$  electrolytes offer a novel approach, resisting carbonation and stabilizing pH, enhancing stability and performance [3]. These trends underscore efforts to improve lithium-ion battery performance, safety, and sustainability, paving the way for efficient, reliable energy storage solutions.

## 7 Conclusion

The survey elucidates the critical influence of electrolyte formulation on the performance and safety of lithium-ion batteries. It reveals that the meticulous selection of electrolyte components—solvents, salts, and additives—plays a crucial role in enhancing ionic conductivity, electrochemical stability, and overall battery efficiency. Recent innovations, including localized high concentration electrolytes and non-flammable gel polymer electrolytes, have shown significant promise in addressing safety concerns by reducing flammability risks and enhancing lithium-ion transport.

Addressing safety challenges such as thermal instability and dendrite formation is essential for improving battery longevity and reliability. The survey emphasizes the necessity of stable solid electrolyte interphases to preserve battery integrity, particularly in high-energy-density systems like lithium-sulfur batteries. Future research directions should prioritize the optimization of molecular design and the development of novel electrolyte formulations with improved thermal stability and safety characteristics. The potential of solid-state battery technologies, alongside innovative recycling methods, offers a pathway toward sustainable and cost-effective battery production. Furthermore, the integration of multiple cation systems and advanced interfacial engineering techniques could significantly enhance battery performance and lifespan.

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## References

- [1] William Manalastas Jr, Sonal Kumar, Vivek Verma, Liping Zhang, Du Yuan, and Madhavi Srinivasan. Water in rechargeable multivalent-ion batteries: An electrochemical pandora's box. *ChemSusChem*, 12(2):379–396, 2019.
- [2] Louis Sieuw, Alia Jouhara, Éric Quarez, Chloé Auger, Jean-François Gohy, Philippe Poizot, and Alexandru Vlad. A h-bond stabilized quinone electrode material for li–organic batteries: the strength of weak bonds. *Chemical science*, 10(2):418–426, 2019.
- [3] Simon Clark, Aroa R Mainar, Elena Iruin, Luis C Colmenares, J Alberto Blázquez, Julian R Tolchard, Arnulf Latz, and Birger Horstmann. Towards rechargeable zinc–air batteries with aqueous chloride electrolytes. *Journal of Materials Chemistry A*, 7(18):11387–11399, 2019.
- [4] Guochun Yan, Kyle Reeves, Dominique Foix, Zhujie Li, Claudio Cometto, Sathiya Mariyappan, Mathieu Salanne, and Jean-Marie Tarascon. A new electrolyte formulation for securing high temperature cycling and storage performances of na-ion batteries. *Advanced Energy Materials*, 9(41):1901431, 2019.
- [5] Dion Hubble, David Emory Brown, Yangzhi Zhao, Chen Fang, Jonathan Lau, Bryan D McCloskey, and Gao Liu. Liquid electrolyte development for low-temperature lithium-ion batteries. *Energy & Environmental Science*, 15(2):550–578, 2022.
- [6] Guinevere A Giffin. The role of concentration in electrolyte solutions for non-aqueous lithium-based batteries. *nature communications*, 13(1):5250, 2022.
- [7] Jens Smiatek, Andreas Heuer, and Martin Winter. Properties of ion complexes and their impact on charge transport in organic solvent-based electrolyte solutions for lithium batteries: insights from a theoretical perspective. *Batteries*, 4(4):62, 2018.
- [8] Oxygen solubility and transport.
- [9] Hansen Wang, Zhiao Yu, Xian Kong, William Huang, Zewen Zhang, David G Mackanic, Xinyi Huang, Jian Qin, Zhenan Bao, and Yi Cui. Dual-solvent li-ion solvation enables high-performance li-metal batteries. *Advanced Materials*, 33(25):2008619, 2021.
- [10] Saul Perez Beltran, Xia Cao, Ji-Guang Zhang, and Perla B Balbuena. Localized high concentration electrolytes for high voltage lithium–metal batteries: correlation between the electrolyte composition and its reductive/oxidative stability. *Chemistry of Materials*, 32(14):5973–5984, 2020.
- [11] Sang Cheol Kim, Xian Kong, Rafael A Vilá, William Huang, Yuelang Chen, David T Boyle, Zhiao Yu, Hansen Wang, Zhenan Bao, Jian Qin, et al. Potentiometric measurement to probe solvation energy and its correlation to lithium battery cyclability. *Journal of the American Chemical Society*, 143(27):10301–10308, 2021.
- [12] Felix Aupperle, Natascha von Aspern, Debbie Berghus, Felix Weber, Gebrekidan Gebresilassie Eshetu, Martin Winter, and Egbert Figgemeier. The role of electrolyte additives on the interfacial chemistry and thermal reactivity of si-anode-based li-ion battery. *ACS applied energy materials*, 2(9):6513–6527, 2019.
- [13] Xiaoli Dong, Yuxiao Lin, Panlong Li, Yuanyuan Ma, Jianhang Huang, Duan Bin, Yonggang Wang, Yue Qi, and Yongyao Xia. High-energy rechargeable metallic lithium battery at -70 °C enabled by a cosolvent electrolyte. *Angewandte Chemie International Edition*, 58(17):5623–5627, 2019.
- [14] Yijie Yin, Yangyuchen Yang, Diyi Cheng, Matthew Mayer, John Holoubek, Weikang Li, Ganesh Raghavendran, Alex Liu, Bingyu Lu, Daniel M Davies, et al. Fire-extinguishing, recyclable liquefied gas electrolytes for temperature-resilient lithium-metal batteries. *Nature Energy*, 7(6):548–559, 2022.
- [15] Yuji Zhang, Yuan Wu, Huiyi Li, Jinghao Chen, Danni Lei, and Chengxin Wang. A dual-function liquid electrolyte additive for high-energy non-aqueous lithium metal batteries. *Nature communications*, 13(1):1297, 2022.

- 
- [16] [www.acsaem.org](http://www.acsaem.org).
- [17] Alfonso J Carrillo, José González-Aguilar, Manuel Romero, and Juan M Coronado. Solar energy on demand: a review on high temperature thermochemical heat storage systems and materials. *Chemical reviews*, 119(7):4777–4816, 2019.
- [18] Mohamed SE Houache, Chae-Ho Yim, Zouina Karkar, and Yaser Abu-Lebdeh. On the current and future outlook of battery chemistries for electric vehicles—mini review. *Batteries*, 8(7):70, 2022.
- [19] Chuanlong Wang, Akila C Thenuwara, Jianmin Luo, Pralav P Shetty, Matthew T McDowell, Haoyu Zhu, Sergio Posada-Pérez, Hui Xiong, Geoffroy Hautier, and Weiyang Li. Extending the low-temperature operation of sodium metal batteries combining linear and cyclic ether-based electrolyte solutions. *Nature Communications*, 13(1):4934, 2022.
- [20] Yonggang Yao, Zhennan Huang, Pengfei Xie, Lianping Wu, Lu Ma, Tangyuan Li, Zhenqian Pang, Miaolun Jiao, Zhiqiang Liang, Jinlong Gao, et al. High temperature shockwave stabilized single atoms. *Nature nanotechnology*, 14(9):851–857, 2019.
- [21] Zhiao Yu, Hansen Wang, Xian Kong, William Huang, Yuchi Tsao, David G Mackanic, Kecheng Wang, Xinchang Wang, Wenxiao Huang, Snehashis Choudhury, et al. Molecular design for electrolyte solvents enabling energy-dense and long-cycling lithium metal batteries. *Nature Energy*, 5(7):526–533, 2020.
- [22] Guangmin Zhou, Hao Chen, and Yi Cui. Formulating energy density for designing practical lithium–sulfur batteries. *Nature Energy*, 7(4):312–319, 2022.
- [23] Aroa R Mainar, Luis C Colmenares, Hans-Jürgen Grande, and J Alberto Blázquez. Enhancing the cycle life of a zinc–air battery by means of electrolyte additives and zinc surface protection. *Batteries*, 4(3):46, 2018.
- [24] Fang Zhang, Yonggang Yao, Jiayu Wan, Doug Henderson, Xiaogang Zhang, and Liangbing Hu. High temperature carbonized grass as a high performance sodium ion battery anode. *ACS applied materials & interfaces*, 9(1):391–397, 2017.
- [25] Zhen Meng, Dominique Foix, Nicolas Brun, Rémi Dedryvère, Lorenzo Stievano, Mathieu Morcrette, and Romain Berthelot. Alloys to replace mg anodes in efficient and practical mg-ion/sulfur batteries. *ACS Energy Letters*, 4(9):2040–2044, 2019.
- [26] Ronny Genieser, Stefania Ferrari, Melanie Loveridge, Shane D Beattie, R Beanland, Houari Amari, G West, and Rohit Bhagat. Lithium ion batteries (nmc/graphite) cycling at 80 c: Different electrolytes and related degradation mechanism. *Journal of Power Sources*, 373:172–183, 2018.
- [27] Zhizhen Zhang, Qinghua Zhang, Jinan Shi, Yong S Chu, Xiqian Yu, Kaiqi Xu, Mingyuan Ge, Hanfei Yan, Wenjun Li, Lin Gu, et al. A self-forming composite electrolyte for solid-state sodium battery with ultralong cycle life. *Advanced Energy Materials*, 7(4):1601196, 2017.
- [28] Ai-Min Li, Zeyi Wang, Taeyong Lee, Nan Zhang, Tianyu Li, Weiran Zhang, Chamithri Jayawardana, Munaiah Yeddala, Brett L Lucht, and Chunsheng Wang. Asymmetric electrolyte design for high-energy lithium-ion batteries with micro-sized alloying anodes. *Nature Energy*, pages 1–10, 2024.
- [29] Marco Agostini, Sergio Brutti, Maria Assunta Navarra, Stefania Panero, Priscilla Reale, Aleksandar Matic, and Bruno Scrosati. A high-power and fast charging li-ion battery with outstanding cycle-life. *Scientific reports*, 7(1):1104, 2017.

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