# Polymer Electrolytes for Improving the Performance and Safety of Lithium-ion Batteries

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**Abstract**

The growing global energy demand coupled with environmental protection measures is driving the need for advanced energy storage technologies capable of storing power generated from renewable sources such as wind, solar and hydropower. This enables broader integration of sustainable energy systems. Among various energy storage systems, batteries have proven to be the most efficient. In particular, Li-ion batteries (LIBs) have emerged as the most reliable and suitable energy storage devices because of their novel characteristics, including high energy density (Ed), high theoretical capacity, compact design and long-lasting performance compared to other storage systems. However, to enhance their energy and power densities and to address safety concerns caused by dendrite growth in the anodes, further optimization is required. Of the three key parts of a battery namely cathode, anode and electrolyte; electrolyte has a vital role, significantly influencing the electrochemical performance and overall operation. In high performance LIBs, solid polymer electrolytes have garnered significant interest because of their enhanced safety, lack of leakage, broad electrochemical stability window, mechanical flexibility and thermal-stability. This paper discusses various types of polymers including PMMA, PEO, PAN, PVDF, PVC, PS and PC, focusing on their synthesis methods and electrochemical performance. The aim is to provide insights into their potential for the advancement in LIB- technology.

**Keywords**: Energy Storage; Li-Ion Batteries; Polymer Electrolytes; Electrochemical Performance.
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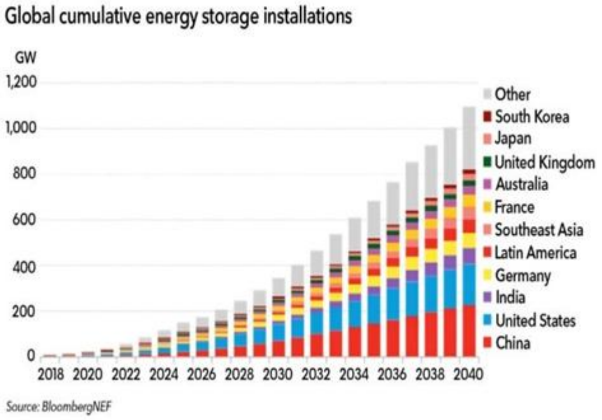
## Introduction

As global energy demand continues to rise, many countries are increasingly turning to various renewable sources. It is projected that 50% of energy demand in the world is expected to be met by renewable sources, especially wind and solar, by 2050 [1]. Fossil fuel use will decrease to 31%, while renewables will account for 62% of energy production. This transition is expected to drive rapid growth in grid support and energy storage, with projections showing a more than 120-fold increase by 2040 according to Bloomberg New Energy Finance (BNEF) [2]. Consequently, the demand for energy storage devices to store power for extended use has become more critical. The demand for energy storage devices across various countries (figure 1) illustrates that the need for such devices can be increased with the expansion of renewable sources. Among different storage devices, lithium-ion batteries (LIBs) play a significant role in most commercially available batteries in the market. They have many advantages such as enhanced energy density (Ed), high operating voltages, long life cycle etc. and it is expected that its global shipments will reach 439.32 GWh by 2025 [3].



Source: BloombergNEF

**Figure 1:** Forecasts for global energy storage installations by 2040 [2].

Among the major components of a battery, current research on anode and cathode materials of LIBs focuses on maximizing energy density and preventing dendrite formation [4]. Most of them, today rely on liquid electrolytes as $Li^+$ conductors, which offers high ionic conductivity and good electrode contact, but presents significant safety risks due to their low thermal stability and flashpoint. Additionally, during $Li^+$ deposition and stripping process, lithium dendrites can form spontaneously and hence, increasing the risk of short circuit. An ideal electrolyte must consider the factors such as conductivity, viscosity, melting point, toxicity and compatibility with electrodes. Altering the electrolyte's chemical or physical properties can significantly enhance safety and improve energy density in LIBs.

To address the challenges in commercial LIBs using liquid electrolyte, non-flammable solid-state electrolytes have been developed. These include inorganic and polymer electrolytes, as well as organic-inorganic hybrid composites. They offer advantages such as high mechanical strength, ionic conductivity exceeding $10^{-4}$ $Scm^{-1}$, negligible electronic conductivity and wide electrochemical stability windows. However, unlike liquid electrolytes, most solid-state electrolytes (SSEs) face difficulties in wetting and penetrating porous cathodes, limiting $Li^+$-conduction inside the cathode and across the electrode/electrolyte interface. Among SSEs, polymer-based variants show higher ability for improving interfacial contact with electrodes and techniques like in-situ polymerization or the insertion of a liquid component offer potential solutions to increase the wetting of thick cathodes [5]. This could lead to solid-state LIBs with higher energy density. This paper presents a comprehensive analysis of polymer-based SSEs, including the synthesis of polymer electrolyte films and the various polymer hosts utilized.

## Synthesis of Polymer Electrolyte Films

Polymer electrolyte films represent an emerging technology with the potential to significantly influence various aspects of our lives, the environment, and the economy. The preparation of film requires the proper selection of polymer matrix, solvent and salt choice. The choice of polymer such as PEO, PVDF, etc. is critical because it is the backbone of the film, providing mechanical strength and flexibility. Selecting a suitable solvent is essential for dissolving the polymer and salts uniformly, whereas the salt provides the mobile ions, usually lithium ions in LIB applications. Some commonly used solvents and salts are acetonitrile (ACN), dimethylformamide (DMF), $LiPF_6$, LITFSI, etc. The preparation of the polymer films can be done by various available methods as given below:

1. **Solution-casting Method:** Solution casting method is a simple and extensively used technique for the fabrication of polymer electrolyte films due to its versatility. It allows easy control over film thickness and is suitable for a wide range of polymers and salts. It follows the steps as mentioned below:
    - The desired amount of polymer is weighed and dissolved separately in the solvent by stirring the mixture for several hours. This process can be carried out at room temperature or at elevated temperatures depending on the polymer's solubility.
    - The required amount of the salt is weighed and then mixed with the dissolved polymer. The mixture is continuously stirred until homogeneous solution is obtained.
    - Formed homogeneous polymer-salt solution is placed in a vacuum chamber for a few minutes to remove any air bubbles.
    - For this, the prepared solution is cast into petri dish.
    - After drying, flexible and self-supporting film is produced.
    - The solvent should be compatible with both the polymer and the salt to produce a polymer film with a thickness ranging from micrometers to millimeters.

2. **Phase Inversion Method:** It is a versatile technique used to fabricate microporous polymer films or membranes. It can be categorized into the following forms:
    - Nonsolvent-induced Precipitation: In this method, a polymer solution is applied to a glass slide and then immersed in a nonsolvent. This causes the polymer to precipitate resulting in thin, porous polymer films. The different porosities formed during this process influence the ion-conductivity of these films. Films with smaller pores and a narrower pore distribution can prevent liquid leakage, while higher porosity is beneficial for achieving higher ionic conductivity.
    - Evaporation-induced Phase Separation: This method involves dissolving a copolymer in a mixed solution of volatile acetone as the solvent and ethanol as the nonsolvent. It is then cast onto a substrate to fabricate a film, which is then air-dried to produce a porous structure. This phase inversion method allows for easy control over the membrane structure enabling the creation of honeycomb or network-like structures.
    - Vapor-induced Precipitation: In this process, precipitation occurs by absorbing a nonsolvent from the vapor phase.
    - Thermally Induced Precipitation: This method involves precipitation by cooling, which causes the polymer to solidify and form a porous structure.

- Each phase separation method offers distinct advantages and allows for the tuning of membrane properties to meet specific requirements.

3. **Spin Coating Method:** This method is similar to the casting technique. Instead of spreading the film across the substrate as in casting, this method involves dropping the mixture onto the substrate and then placing it in a spin coater. The spin coater rotates at a variable speed, allowing precise control over the film's thickness by adjusting both the mixture's viscosity and the rotation speed. However, this technique is effective when the mixture's viscosity is relatively low. For gel-like mixtures, the spinning action alone is insufficient to spread the droplet into a thin-film.

4. **Hot Press Method:** In this method, polymer and salt are first combined in a mortar to form a fine powder through several minutes of mixing. This powder mixture is then placed between two Mylar sheets or similar materials and positioned in a heating chamber to set a temperature slightly above the polymer's melting point. The sample is pressed overnight using a weight-controlled pressure. After the pressing and heating process, it is gradually cooled to room temperature. Finally, it is removed from the Mylar sheets and transferred to a glove box.

## Polymer Electrolytes

Polymer electrolytes consisting of a polymer host and a lithium salt with low lattice energy and large anions, function as electrolytes by dissolving within a polymer matrix. Ionic conduction in these materials is driven by the covalent interaction between the polymer and ionizing groups. Initially, polymer's electron-donating groups solvate the cation from the dopant salt, facilitating ion separation and ionic hopping, which generates conductivity. In conventional batteries, electrolytes and separators assist the ion movement between electrodes, but polymer electrolytes can replace both components in solid-state configurations. Polymer electrolytes are highly valued for their ability to accommodate electrode volume changes, improve current density, enhance safety, and reduce dendrite formation. However, their lithium-ion conductivity at room temperature remains low, though advancements like blending and modified derivatives have improved high performance. Key requirements for polymer electrolytes include ionic conductivity ($> 10^{-4}$ Scm$^{-1}$), electrical insulation, low activation energy, excellent thermal and chemical stability, high cation transference and compatibility with electrode materials. Additionally, they should be non-toxic, cost-effective, have a wide operational temperature range as well as both low melting point and high boiling point for optimal battery performance [6].

## Ionic Conduction Mechanism in Polymer Electrolyte

Ionic conduction in polymer electrolytes is a complex process that depends on the structural dynamics of the polymer matrix and the interaction between lithium ions ($Li^+$) and polymer functional groups. The conduction mechanism is basically determined by the polymer's amorphous and crystalline phases, polymer-segment mobility and the formation of ion-conducting pathways.

1. **Polymer-Salt Complexation and Ion Dissociation** [7]: In polymer electrolytes, $Li^+$ ions coordinate with polar functional groups such as ether oxygens in poly (ethylene oxide) (PEO) or nitrile groups in polyacrylonitrile (PAN). The dissolution of lithium salts within the polymer matrix results in the formation of mobile charge carriers ($Li^+$ and anions), which are essential for ionic conduction.

2. **Segmental Motion and Ion Transport** [8]: The local movement of polymer chains greatly impacts the mobility of $Li^+$ ions. In the amorphous phase, polymer segments undergo dynamic relaxation, allowing $Li^+$ ions to hop between coordinating sites. This process is known as segmental-assisted transport and it involves the breaking and reforming of Li–polymer bonds in order to facilitate ion migration. Higher is the polymer flexibility, better is the ionic conductivity.

3. **Inter- and Intra-chain Hopping Mechanisms**: Ionic conduction occurs through three primary pathways [9]:
   - Intra-chain motion: $Li^+$ ions move along a polymer chain through weak coordination with functional groups.
   - Polymer-segment relaxation: The movement of polymer segments influences ion transport by modifying the polymer environment.
   - Inter-chain hopping: $Li^+$ ions jump from one polymer chain to another, enabling long-range ion diffusion.

4. **Crystalline vs. Amorphous Transport**: While it was assumed that only the amorphous phase contributes to ionic transport, recent studies have shown that crystalline polymer structures can also support ion migration. In crystalline PEO/$LiXF_6$ complexes [10], $Li^+$ ions move through cylindrical tunnels formed by folded polymer chains, offering a static pathway for conduction without requiring segmental motion. However, ionic transport is generally more efficient in the amorphous phase due to higher polymer flexibility.

5. **Glass Transition Temperature Dependence ($T_g$)**: Ionic conductivity is closely related to the polymer's

$T_g$. Below $T_g$, the polymer chains are rigid, restricting ion mobility and leading to poor conductivity. Above $T_g$, the polymer matrix transitions into a rubbery state, enhancing the flexibility of chains and facilitating faster ion transport [11].

## Types of Polymer Electrolytes

These can be classified in the following types based on their physical state and composition:

1. **Gel Polymer Electrolytes (GPEs):** These consist of a polymer host swollen with liquid electrolyte. While maintaining a semi-solid form, GPEs exhibit higher ionic conductivity due to the liquid component, while still offering some mechanical strength. They are widely used in LIBs for balancing conductivity and safety.

2. **Composite Polymer Electrolytes (CPEs):** These are a hybrid form, combining a solid polymer electrolyte with ceramic or inorganic fillers to enhance mechanical properties and ionic conductivity. CPEs aim to improve conductivity, stability, and overall performance by leveraging both the polymer matrix and solid particles.

3. **Perovskite-type Polymer Electrolytes**: Perovskite-type polymer electrolytes combine the high ionic conductivity of perovskite ceramics, such as lithium lanthanum titanium oxide (LLTO), with the flexibility of polymers like poly (ethylene oxide) (PEO) and poly (vinylidene fluoride) (PVDF). Perovskite materials typically exhibit high lithium-ion conductivity, ranging from $10^{-3}$ to $10^{-4}$ S/cm at room temperature, while maintaining extremely low electronic conductivity, around $10^{-8}$ S/cm [12]. This balance makes them excellent candidates for solid-state electrolytes, as they efficiently transport lithium ions while minimizing electronic leakage, which is crucial for battery performance and safety. Blending perovskites with polymers enhances mechanical stability and interfacial compatibility, leading to improved performance in lithium batteries.

4. **Sulphide-type Polymer Electrolytes**: Sulphide-type polymer electrolytes combine highly conductive sulphide materials with flexible polymers to improve performance in solid-state lithium-ion batteries. Sulphide-based electrolytes, like lithium phosphorus sulphide (LPS) and lithium argyrodite ($Li_6PS_5X$, X = Cl, Br, I), are known for their excellent ionic conductivity and good electrochemical stability. However, they are brittle and highly sensitive to moisture, making them difficult to use on their own. Blending sulphide particles with polymers such as poly (ethylene oxide) (PEO) or polyacrylonitrile (PAN) improves mechanical flexibility and enhances compatibility with battery electrodes [13].

5. **Solid Polymer Electrolytes (SPEs):** These are composed of a polymer matrix with dispersed lithium salts and have been widely studied for applications in LIBs and other electrochemical systems. The ions are transported through the polymer structure, which remains in a solid state. Solid polymer electrolytes (SPEs) must provide good mechanical strength, safety, thermal stability, ionic conductivity, and electrochemical stability to prevent lithium dendrite growth. There are various host polymers are in use for the synthesis of polymer-electrolytes. Key properties of polymer hosts are [14]:
   - Electron donor groups (O, N, P, S) for coordinating with Li+-ions.
   - Fast segmental motion of polymer chains to enhance ionic conductivity.
   - Low Tg (glass transition temperature).
   - Elevated thermal decomposition temperature.
   - Larger molecular size.
   - Optimal spatial configuration for salt dissociation.
   - Appropriate distance between coordinating centres to avoid intra-polymer ion bonding.
   - Sufficient flexibility for enhanced performance.

## Different Types of Polymer Host

Various types of polymer hosts are being researched for polymer electrolytes due to their ability to dissolve lithium salts and support ionic conduction (Table 1). Some of them are explained below:

1. **Polyethylene Oxide (PEO):** It is a leading candidate for SPEs in LIBs due to its ability to form complexes with metal salts, low cost and easy production. It is discovered in 1973 by Wright, PEO exhibits ionic conductivity with $Li^+$ salts, driven by its flexible ethylene oxide chains, high electrochemical stability and strong dielectric properties [15,16]. However, its semi-crystalline nature limits ionic-conductivity at room temperature and low $Li^+$ transference-number affect battery performance [17]. To address these issues, various strategies have been investigated to enhance ionic conductivity and interfacial properties. These include addition of plasticizer with high dielectric constant and incorporation of inorganic filler into PEO-based polymer-electrolyte to simultaneously improve ionic-conductivity and mechanical stability [5]. Additionally, blending with other polymers like PAN and PVDF, known for their favourable mechanical properties, to further strengthen the

mechanical stability of PEO-based electrolytes [18-19].

2. **Polyacrylonitrile (PAN):** PAN-based lithium salt complexes are known for their strong ionic conductivity, stable thermal property, mechanical strength and compatibility with electrode materials used in LIBs. PAN's semi-crystalline structure dissolves various lithium salts and effectively absorbs electrolytes. The addition of plasticizers enhances ion mobility, increasing conductivity to $1.7\times10^{-3}$ $Scm^{-1}$ at 20 °C and $1.1\times10^{-3}$ $Scm^{-1}$ at 10 °C [18]. The PAN based gel electrolyte has transference number more than 0.5, which can be increased to 0.7 by adding lithium bis (trifluoromethyl sulfonyl) imide (LiTFSI) and lithium bis (trifluoro methane sulfonyl) methide (LiTFSM) salts addition [20]. However, PAN's high electrolyte absorption can lead to swelling and passivation at the lithium electrode interface, impacting battery performance. Blending PAN with polymers like polyethylene oxide (PEO) improves ionic-conductivity, mechanical flexibility, and interfacial characteristics, making it more suitable for LIBs [21].

3. **Polymethylmethacrylate (PMMA):** It is a thermoplastic with good dimensional stability and high lithium-ion affinity, but its brittleness limits its use in flexible, solid-state devices. Initially used as a gelling agent, PMMA-based electrolytes exhibit moderate ionic conductivity with improvements observed when blended with other polymers or doped with lithium salts like LiTFSI [22]. It has been observed that combining PMMA with PVC enhances mechanical strength, while the addition of silica nanoparticles or ionic liquids to PMMA/LiTFSI further increases its conductivity to $2.44 \times 10^{-6}$ $S\cdot cm^{-1}$ when prepared using the solution casting technique.[14]. Copolymerization and blending with materials like poly (vinylidene fluoride-hexafluoro propylene) and LLZN nanowires can also enhance performance making PMMA a versatile component in electrolyte formulations.

4. **Polyvinylidene Fluoride (PVDF):** It is a semi-crystalline polymer known for its high dielectric constant (~8.4) and anodic stability, attributed to its strong electron-withdrawing (–C–F) groups [6]. This characteristic enhances salt dissolution and increases charge carriers' concentration. PVDF-based electrolytes exhibit varying ionic conductivities, with improvements observed when plasticizers like propylene carbonate (PC) are added. For instance, PVDF with 30 mol% $LiClO_4$ and PC shows significant conductivity enhancement, reaching $1.74\times10^{-3}$ $S\ cm^{-1}$ at 30 °C [23]. Blending PVDF with lithium nitrate or phthaloyl starch can further improve ionic conductivity and electrochemical stability, though PVDF's interfacial stability with lithium remains a challenge.

5. **Polyvinyl Chloride (PVC):** PVC is another polymer host known for its chemical resistance, flexibility, and mechanical strength, making it suitable for creating durable electrolyte membranes. However, it often requires plasticizers to improve ion transport. Studies have shown that PVC complexes with LiTFSI, plasticized using dibutyl phthalate and dioctyl adipate, exhibit significantly enhanced ionic-conductivity as the PVC content decreases. These complexes also achieve an electrochemical stability window of ~ 4.0 V at 60°C [24]. Despite its advantages, PVC-based polymer electrolytes face challenges such as solvent exudation. This issue can be addressed by substituting PVC with a PVAC copolymer. Furthermore, instead of using auxiliary carrier solvents like tetrahydrofuran (THF) for PVC or PVAC, direct utilization of solvents has been suggested as a viable alternative [25].

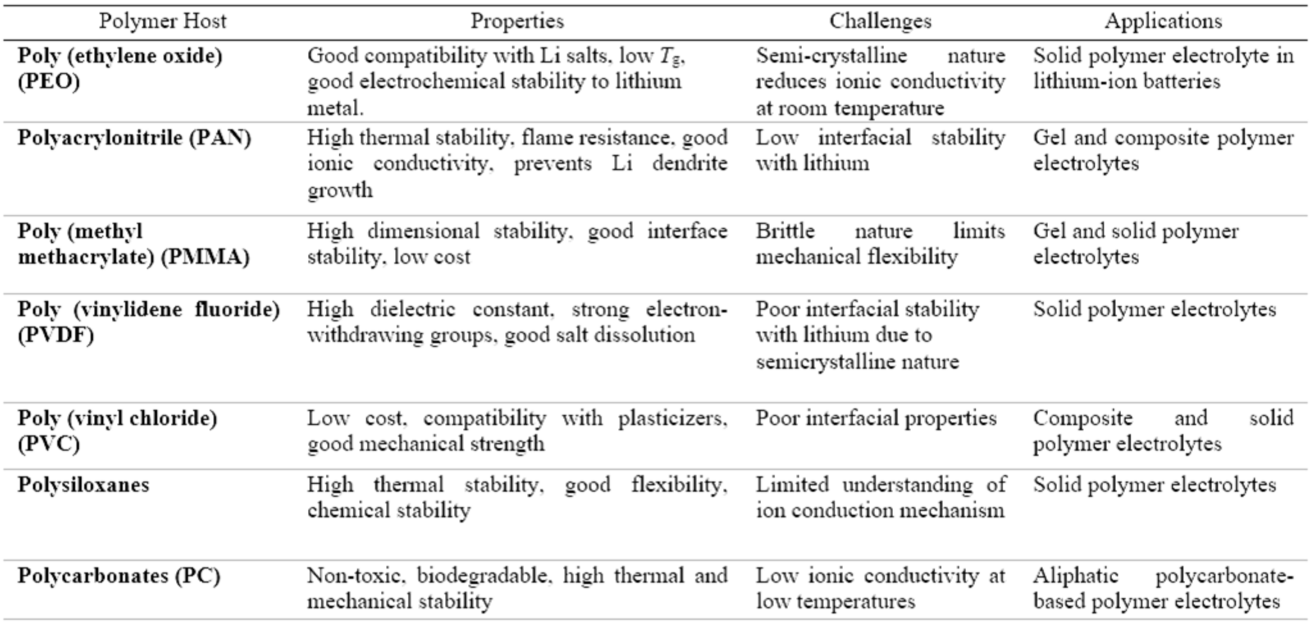
6. **Polysiloxane (PS):** Polysiloxanes are known for their low temperature ($T_g$), significant free space, excellent electrochemical stability and flexibility [26]. Their amorphous nature allows for good ionic conductivity, especially when blended with other polymers or plasticizers.

7. **Polycarbonate (PC):** Polycarbonate polymers have gained attention as promising hosts in LIBs, especially for applications in solid-state and gel polymer electrolytes. These materials provide a balance of mechanical strength, ionic-conductivity and electrochemical robustness, making them ideal candidates for advanced energy storage technologies. Solid polymer electrolytes developed using aliphatic polycarbonates—such as poly (ethylene carbonate) and poly (propylene carbonate)-demonstrate enhanced ionic-conductivity, electrochemical stability and thermal resilience. This is attributed to their amorphous structure, high dielectric constant and flexible chain segments, which collectively contribute toward improved performance [6].

Each polymer host has its strengths and challenges and they are often modified or combined with other materials to enhance properties such as ionic conductivity, mechanical stability and thermal stability for use in LIBs.

## Applications of Polymer Electrolytes in Lithium-based Batteries

**Table 1:** Comparison of Polymer Host for Solid State Electrolytes based on their associated challenges and applications.



| Polymer Host | Properties | Challenges | Applications |
|---|---|---|---|
| **Poly (ethylene oxide) (PEO)** | Good compatibility with Li salts, low $T_g$, good electrochemical stability to lithium metal. | Semi-crystalline nature reduces ionic conductivity at room temperature | Solid polymer electrolyte in lithium-ion batteries |
| **Polyacrylonitrile (PAN)** | High thermal stability, flame resistance, good ionic conductivity, prevents Li dendrite growth | Low interfacial stability with lithium | Gel and composite polymer electrolytes |
| **Poly (methyl methacrylate) (PMMA)** | High dimensional stability, good interface stability, low cost | Brittle nature limits mechanical flexibility | Gel and solid polymer electrolytes |
| **Poly (vinylidene fluoride) (PVDF)** | High dielectric constant, strong electron-withdrawing groups, good salt dissolution | Poor interfacial stability with lithium due to semicrystalline nature | Solid polymer electrolytes |
| **Poly (vinyl chloride) (PVC)** | Low cost, compatibility with plasticizers, good mechanical strength | Poor interfacial properties | Composite and solid polymer electrolytes |
| **Polysiloxanes** | High thermal stability, good flexibility, chemical stability | Limited understanding of ion conduction mechanism | Solid polymer electrolytes |
| **Polycarbonates (PC)** | Non-toxic, biodegradable, high thermal and mechanical stability | Low ionic conductivity at low temperatures | Aliphatic polycarbonate-based polymer electrolytes |

Polymer electrolytes are emerging as a key solution for enhancing the performance, safety and longevity of lithium-based batteries. Their unique combination of flexibility, lightweight properties, and improved interfacial stability makes them ideal for next-generation energy storage systems. Some of the most promising applications include:

1. **Solid-state Lithium-ion Battery:** Solid-state lithium-ion batteries (SSBs) are gaining attention for their ability to replace traditional liquid electrolytes with solid polymer electrolytes, making them safer, more energy-dense and long-lasting. They are particularly promising for electric vehicles (EVs) and grid energy storage due to their stability and high energy capacity. Recent advancements have further improved their performance-Wang et al. [27] developed an electrospun solid polymer electrolyte (SPE) using a bio-polyamide (IBD) blended with PEO/Li bis(trifluoromethanesulfonyl)imide, achieving strong lithium-ion transport and an impressive ionic conductivity of $4.26 \times 10^{-4}$ S/cm at 50°C. Meanwhile, Zhu et al. [28] introduced an inorganic-polymer gel electrolyte incorporating helical mesoporous silica nanofibers (HMSFs), leading to remarkable thermal stability (up to 372°C), a wide electrochemical window (5.30 V), and high ionic conductivity at room temperature ($1.2 \times 10^{-3}$ $Scm^{-1}$). These innovations bring us closer to safer, more efficient batteries that could revolutionize energy storage and transportation.

2. **Lithium-Metal Batteries (LMBs):** LMBs are a promising next-generation energy storage technology due to their high energy density, making them ideal for long-lasting applications. However, they face safety challenges, particularly dendrite formation, which can cause short circuits. To improve safety and performance, researchers are developing advanced electrolytes. A recent study by Xie et al. [29] introduced a gel polymer electrolyte (GPE) called AT11-GF, which uses a non-flammable material to enhance lithium-ion conduction. By adding a protective film-forming agent, they improved stability and compatibility with the lithium anode, achieving high ionic conductivity and long-lasting performance. These advancements bring us closer to safer and more efficient lithium-metal batteries.

3. **Lithium-air (Li-air) Batteries:** They are also known as lithium-oxygen batteries and are an emerging energy storage technology that uses oxygen from the air as the cathode material. They have the potential to achieve extremely high energy density, making them attractive for applications like electric vehicles and aerospace. Polymer electrolytes play a vital role in these batteries by providing a stable and efficient pathway for lithium-ion transport. Recent advancements, such as the gel polymer electrolyte (GPE) introduced by Yoon et al. [30], have significantly improved ionic conductivity, lithium stability and redox activity, leading to longer cycle life and higher capacity. Additionally, research by Song et al. [31] demonstrated that using a 3D garnet network composite polymer electrolyte enhances the performance of solid-state Li-air batteries, paving the way for more efficient and durable energy storage solutions.

4. **Lithium-Sulphur Battery:** Polymer electrolytes are being explored for lithium-sulphur (Li-S) batteries, which have a sulphur-based cathode and offer high

energy density, making them ideal for electric vehicles and renewable energy storage. One major challenge with Li-S batteries is stability, but recent research has led to significant improvements. For example, adding special polymers like poly(sulfur-1,3-diisopropenylbenzene) (PSD) into a P(VDF-HFP) polymer matrix has helped to improve ionic conductivity. Scientists have also developed flame-retardant polymer electrolytes to make these batteries safer. Another breakthrough involves using in situ electrochemical polymerization to create a non-flammable polyether electrolyte, which enhances lithium compatibility and improves battery performance. These innovations have led to higher capacity, faster charging, and longer battery life, making Li-S batteries a promising option for the future [32].

## Fundamental Challenges in Lithium-ion Batteries

The development of next-generation lithium-ion (Li-ion) batteries faces several fundamental challenges that must be addressed to improve energy density, longevity and safety.

1. **Electrode-Electrolyte Interface Stability:** The formation of a stable solid electrolyte interphase (SEI) is crucial for battery performance, yet its composition and long-term stability remain poorly understood. Electrochemical side reactions with high-capacity cathodes can degrade electrolytes, reducing efficiency.

2. **Dendrite Formation and Safety Risks:** Lithium metal anodes can develop dendrites, which may lead to short circuits, overheating or even battery failure. Advanced solid-state electrolytes or protective coatings are needed to mitigate this issue.

3. **Limited Cycle Life:** High-capacity electrode materials, such as silicon and tin, suffer from significant volume expansion and contraction during charge-discharge cycles, causing mechanical stress and cracking, which reduces battery lifespan.

4. **Electrochemical-Mechanical Coupling:** Mechanical failure due to expansion, stress, and defects in solid-state electrolytes can hinder ion transport and overall battery performance. Understanding how electrochemical and mechanical properties interdepend is essential for improving battery durability.

5. **Fast Charging Limitations:** High charging rates can lead to lithium plating on the anode, reducing efficiency and increasing safety risks. New materials and electrolyte formulations are needed to enable safer and faster charging.

6. **Environmental and Cost Constraints:** The reliance on expensive and resource-limited materials like lithium, cobalt and nickel raises concerns about sustainability. Developing cost-effective recycling methods and alternative battery chemistries is crucial for large-scale adoption.

Addressing these challenges requires innovations in material science, interface engineering and electrolyte design to push Li-ion technology toward safer, more efficient and long-lasting energy storage solutions.

## Summary and Future Prospective

In this paper, the critical role of polymer-based electrolytes in the advancement of LIB technology has been analysed. The increasing demand for renewable energy sources needs high-performance, safe and reliable energy storage solutions. Traditional liquid electrolytes have enabled LIBs to achieve significant energy densities, but these electrolytes come with safety constraints. Polymer electrolytes offer promising potential to improve the safety and efficiency of LIBs by reducing dendrite growth and enhancing stability. This paper analyses the properties and synthesis methods of various polymer hosts, highlighting how each material contributes to enhanced ionic conductivity and thermal stability are also analysed in detail.

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