Role of Solid – State Electrolytes in Lithium Ion Battery

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How to Cite this Article:

Krishan, K. (2026). Role of Solid – State Electrolytes in Lithium Ion Battery. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(9), 1-9. https://doi.org/10.55041/ijcope.v2i9.157

https://doi.org/10.55041/ijcope.v2i9.157

ABSTRACT

With an emphasis on recent developments in solid electrolytes and anodes, the main objective of this review is to present a thorough overview of the state-of-the-art in solid-state batteries (SSBs). The paper opens with a background on the transition from liquid electrolyte lithium-ion batteries to advanced SSBs, stressing their enhanced safety and energy density. It responds to the growing need for effective, secure energy storage in devices like portable gadgets and electric cars. The analysis of solid electrolytes, which are essential to SSB technology, takes up a significant portion of the text. Solid electrolytes are categorised as polymer-based, oxide-based, and sulphide-based, and their unique characteristics and appropriateness for various applications are discussed. The paper also discusses developments in anode materials for SSBs, examining materials like as silicon, lithium metal, and intermetallic compounds with an emphasis on their durability, capacity, and compatibility with solid electrolytes. It tackles issues like interface stability and lithium dendritic development that arise when integrating these anode materials. The most recent analytical methods, experimental research, and computational models to comprehend and enhance the anode–solid electrolyte interface are discussed in this review. These are essential for addressing interfacial resistance and guaranteeing the long-term stability and effectiveness of SSBs. The study's conclusion highlights the potential of SSBs to transform energy storage technologies and makes recommendations for future research and development paths. For scholars, researchers, and business executives involved in the development of advanced battery technology, this review is an essential resource. It provides a thorough summary of the materials and technologies influencing the future of SSBs, offering insights into present issues and possible fixes in this quickly developing industry.

Keywords: Solid-state batteries (SSBs), Solid electrolytes, Anode materials, Interfacial stability Lithium dendrites, Lithium metal, Interfacial resistance, Polymer/oxide/sulphide electrolyte Energy density, Energy storage.

1.Introduction

The development of sustainable energy systems has been greatly aided by the advancement of modern technological capabilities, which has been made possible by the evolution of energy storage technologies [**1,2**]. Energy storage has had several stages of invention throughout history, all of which have improved its effectiveness, safety, and environmental impact [**3**]. Solid-state energy storage is currently undergoing a significant shift, as demonstrated by the creation and application of solid-state batteries (SSBs). The realisation of the shortcomings of conventional energy storage systems, especially those that use liquid electrolytes, such as lithium-ion batteries (LE-LIBs), and significant advancements in materials science, which have introduced new materials and fabrication methods essential for solid-state energy storage systems, are the two primary causes of this change [**4,5,6**].

Using solid electrolytes, SSBs provide higher energy densities, which are essential for a variety of applications, including consumer electronics and electric cars ,they also naturally lower many of the safety issues associated with liquid electrolytes [**4,7**]. Additionally, the use of more robust and chemically stable electrode materials is made possible by solid electrolytes, which increases battery longevity and efficiency [**8**].

Despite their high energy density and extensive use, liquid electrolyte lithium-ion batteries are becoming increasingly limited in terms of performance, safety, and environmental effect,the flammability of liquid organic electrolytes, the possibility of thermal runaway, the production of dendrites during charging, and temperature-dependent ionic conductivity that affects battery longevity and performance are among the issues [**9,10**]. Environmental and social issues are also raised by the extraction of elements like cobalt and lithium, as well as by the recycling and disposal of these batteries at the end of their useful lives [**11**].In light of these limitations, there is increasing interest in investigating substitutes such as SSBs, which offer enhanced performance, increased safety, and environmental compatibility, the development of high-voltage cathodes and anodes may be encouraged by the switch to solid-state electrolytes in SSBs, which could increase the energy density and expand the operating voltage window [**12,13**].

We focus on the important transition from liquid-based to solid-state systems in this thorough analysis, emphasising the major scientific and technical developments that have sparked this change [**14,15**]. We will examine the urgent need for more effective energy storage solutions, the limitations of existing technologies, and the advances in material science that have made solid-state options possible, our goal is to provide a thorough grasp of the fundamental changes altering energy storage technologies, even though we cover a wide range of complex systems, In order to clarify the creative advancements in this specific field of energy storage technology, we will mainly concentrate on the significant advancements in solid electrolytes and anode materials for solid-state batteries (SSBs), with a particular focus on lithium-metal anodes and their interfaces [**16,17,18**].

2.LITHIUM ION BATTERY

The essential power source for contemporary electric cars is the lithium-ion battery, compared to other commercially available batteries, it has a higher energy density and is rechargeable [**19, 20**]. It is also utilised in computers, smartphones, and other devices because of its low weight, each battery is made up of several batteries, which are referred to as cells. Conductive surfaces allow the electric current to enter the cells [**21,22,23**]. The most common conducting surfaces for these batteries are copper and aluminium, its cathode (+) and anode (−) electrodes are positive and negative, same as those of conventional batteries [**24**].

The Very pure lithium oxide ($LiMO_2$; M=Co, Ni) makes up the cathode, a positive electrode. Its performance and battery life are improved when its chemical makeup is more homogeneous [**25**]. Graphite, a type of carbon layer structure, makes up the negative electrode (anode), which is positioned on the opposite side. Because of its inexpensive cost, natural availability, high coulombic efficiency, and flat potential profile while charging and discharging, graphite has been a common anode material for commercial lithium-ion batteries. In addition to the lithium alloys offer greater energy density than commercial Li-intercalated carbons because of their increased Li storage capacity [**26,27,28**].

Both the anode and the cathode have high capability rates; however, the cathode frequently limits the cells' cycle life [**29**]. Its high electrical resistance or the slow movement of Li+ ions within the solid phase could be the cause of the unexpectedly low cathode power competence (as mentioned before, the metal dissolution from the cathode is also considerably accelerated at increasing temperatures), To allow the lithium-ion carrying charge to travel freely, the battery is constructed with a transport medium (the electrolyte). this electrolyte needs to be very pure, a layer known as a separator is positioned between two electrodes to prevent short circuits, the small lithium ions can pass through the separator [**30,31,32**]. this characteristic was dubbed "micro-porosity" by the specialists, positively charged lithium ions are kept in the layered graphite anode structure after moving from the cathode through the separator during the charging process [**33**]. Conversely, the battery loses energy when it discharges, through the separator, the electrolyte returns the lithium ions to the cathode, the car runs because the motor transforms electric energy into mechanical energy, it is not a one-way energy conversion process, electrical energy can also be transformed into chemical potential and stored in a system [**34,35**]. The schematic of a lithium-ion battery shown below.

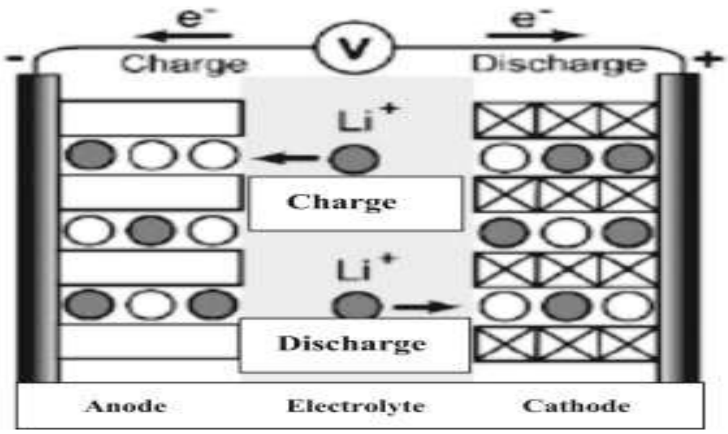


Figure1:
https://www.sciencedirect.com/topics/materials-science/lithium-ion-battery

$e^- + M^+ \leftrightarrow M$

The quality of the material utilised has a direct impact on the energy's availability and battery life, to put it another way, improved performance and longer battery life result from higher-quality pure materials combined with a customised formulation, As previously stated, this battery's high energy density allows it to store more energy per unit mass or volume than conventional batteries—nearly twice as much as nickel-cadmium batteries, Until the battery runs out, it can be recharged. additionally, there is no memory effect, thus they don't need to be fully discharged before being recharged, it has a limited amount of time to retain its charge (5% energy loss per month), Even a battery with a high energy density has some drawbacks, It is extremely susceptible to high temperatures and has a short lifespan of two to three years from the date of manufacture. The separator may catch fire if it sustains damage [**36,37,38,39,40**]

3. STRUCTURE AND WORKING PRINCIPLE OF LITHIUM-ION BATTERIES

Electrochemical reactions, particularly redox reactions involving lithium and occasionally other redox-active materials, are the basis for the operation of lithium-ion batteries [**41**]. Lithium ions pass between the electrodes because of these processes, and electrons move through an external circuit, depending on whether the battery is charging or discharging, lithium ions intercalate into the electrode materials during operation [**42**]. The insertion of lithium ions into the electrode material's crystal or molecular structure is referred to as intercalation, lithium ions originate from cathode active materials, while anode active materials house them while they are charged [**43**]. To keep the battery safe and effective, the electrode materials must be able to accommodate lithium ions without undergoing substantial structural or volume changes.

The figure 2 illustrate that the Lithium ions can move through a lithium-ion battery thanks to a number of crucial parts, the lithium ions are supplied by cathode active materials rich in lithium, such as lithium cobalt oxide and lithium iron phosphate [**44,45,46**]. Anode active materials usually have a high capacity and a low voltage (electrochemical potential vs. Li/Li+) [**47**].

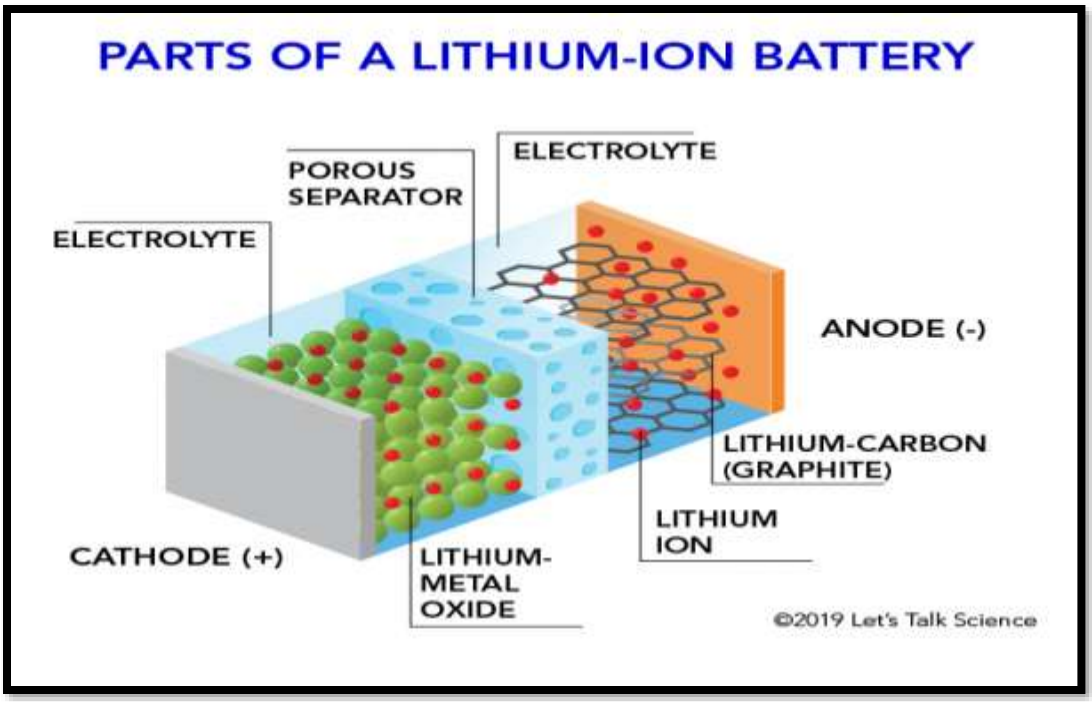


Figure 2: Lithium-ion battery **Source:** https://letstalkscience.ca/

By maintaining the electrodes' electrical isolation, a non-conductive electrolyte and separator stop short circuits, the current collectors gather the electrons that lithium releases during oxidation at the electrodes and move them via an external circuit, Additionally, these materials allow lithium-ion transfer while confining the electrons to the electrodes or external circuit [**48,49**].

3.1. Lithium-Ion Batteries Working

Electrochemical processes are how lithium-ion batteries function. Lithium ions are forced through the electrolyte and into the anode material by applying a voltage to a battery, the anode is the site of lithium-ion reduction because of its low electrochemical potential, which attracts lithium ions [**50,51**]. lithium Electrochemical Reactions,

Oxidation: $Li \rightarrow Li^+ + e^-$ **Reduction:** $Li^+ + e^- \rightarrow Li$

The oxidation of lithium provides access to electrons that can be used to power a device as part of the external circuit. Conversely, the reduction of lithium ions during charging enables energy to be stored at the anode, other redox-active metals, such as nickel and cobalt, within cathode materials may also undergo redox reactions. Nickel can participate in multi-electron redox processes, which contributes to increased energy capacity in the battery [**52,53**]. Rechargeable batteries are in a discharged condition when they are put together, connecting lithium-ion batteries to a power source allows them to be charged, the intercalated lithium ions in the cathode are moved in the direction of the anode by the applied voltage [54].

3.2. Charging Lithium-Ion Batteries:

Because of the potential difference between the two electrodes, lithium ions move from the cathode to the anode during charging. An external circuit drives Li+ ions via the electrolyte to the anode, where the electrons are building up. Charge storage is made possible by the simultaneous build-up of Li+ ions and electrons at the anode, The lithium ions are reduced back to neutral lithium atoms after intercalation into the anode material, which is usually graphite. Reduction is made possible by electrons that have accumulated at the anode through the external circuit [**42,55**].

3.3. Discharging Lithium-Ion Batteries:

A circuit is powered by the charged lithium-ion battery, which causes the battery to discharge. When the gadget discharges, electrons go from the anode to the cathode via a circuit, giving it electricity. Concurrently, lithium is oxidised at the anode, and lithium ions return to the cathode material via the electrolyte. The battery needs to be charged to be utilised once all the lithium ions have intercalated with the cathode [**56,57**].

3.4. Materials for Cathodes

Battery research has largely focused on the cathode material since it is the most restricted of the four main components. In the majority of lithium-ion batteries, the cathode is crucial to the ion supply. Therefore, study is essential to determine the optimal shape and chemistry for each distinct battery application [**58,59**].

The most common cathode materials include - Lithium iron Phosphate, Lithium Cobalt Oxide, Lithium Nickel Manganese, Lithium Nickel Manganese Cobalt Oxide

3.5. Materials for Anodes

The anode must be isometric and provide a high discharge voltage. Graphite is frequently utilised. Because of its porous nature and broad discharge profile, lithium ions can interact with the structure during charging and vice versa, graphite or hard carbon are now the most widely used anode materials; however other anode materials are being tested. Although they have a larger charge capacity, they often expand or compress when being charged, seventy to eighty percent active material, ten to fifteen percent conductive binder (such as carbon black or acetylene black/Super P), and five to fifteen percent polymer binder (such as polyvinylidene fluoride, or PVDF) make up composite anodes [**60,61,62**].

Common anode materials include- Cobalt black Nanopowder, Graphite Nanopowder, Lithium Titanium Oxide, Carbon Black Powder, Graphite powder.

3.6. Electrolytes

The electrolyte carries lithium ions from the cathode to the anode, and vice versa, without allowing a flow of electrons. It is important to consider the chemical and physical reactions that could occur between the electrolyte and other battery components [**63**]. The electrolyte must be chosen carefully to prevent voltage induced electrochemical decomposition or rapid oxidation. Generally, electrolytes are a mix of electrolyte salts in either an organic or inorganic solvent. Electrolytes are also available in either an aqueous or solid solution, although solid electrolytes are a fairly new research area. Solid state electrolytes are emerging as a new substitute for aqueous solutions. They have a higher energy density and improved safety, through a larger range of operating temperatures and dendrite prevention [**64,65,66**].

3.7. Separator

Ion travel is moderated by the separator material's inherent safety feature and structural integrity. The separator is made to close or open its pores in response to temperature because thermal runaway could occur if ions flow through the electrolyte too quickly [**67**].The construction of separators to aid in the prevention of dendritic and solid electrolyte interphase development is an intriguing field of study [**68**]. This increases the battery's lifespan. A spike-like development may result from an uneven distribution of lithium ions passing through the separators, raising the possibility of penetration and short circuiting. The battery's life can be extended by keeping the dendritic development uniformly dispersed by the maintenance of a uniform ion distribution [**69**].

4. ELECTROLYTES IN LITHIUM-ION BATTERIES

The electrolyte of a lithium-ion battery acts as the essential circulatory system that keeps the battery running. To transport positively charged lithium ions (Li^+) back and forth during cycles of charging and discharging, it is a conductive chemical medium placed between the positive electrode (cathode) and the negative electrode (anode) [**70**]. Your device is powered by electrons carried by the external circuit, but internal electron flow is absolutely prohibited by the electrolyte. The battery would short circuit if electrons could flow through the electrolyte. Consequently, a good electrolyte needs to have high electrical resistance to push electrons through the external circuit and high ionic conductivity to transfer lithium ions effectively [71].

4.1. Chemical Composition:

Since the operating voltage of commercial lithium-ion batteries greatly exceeds the electrochemical stability window of water (which would simply undergo electrolysis), the usual electrolyte used in these batteries is a non-aqueous liquid solution [**72,73**]. Lithium salt is dissolved in a mixture of organic carbonate solvents to create this solution. Lithium hexafluorophosphate (LiPF6) is the most often used salt because of its superior ionic conductivity balance [**74,75**]. Electrochemical stability and the capacity to passivate the cathode-side aluminium current collector. Engineers utilise a co-solvent mixture because lithium salts need a polar solvent to dissolve, while the battery needs a low viscosity solvent for quick ion movement [**74,76**]. A low-viscosity solvent, such as Dimethyl Carbonate (DMC) or Diethyl Carbonate (DEC), is added to ensure that the ions may physically pass through the liquid with little resistance, while a high-dielectric solvent, such as Ethylene Carbonate (EC), is employed to successfully dissociate the lithium salt [**77**].

4.2. The Ion Transport Mechanism

The graphite anode's lithium atoms lose an electron when a lithium-ion battery discharges. After entering the electrolyte, the resultant Li+ ion is instantly encircled by solvent molecules, creating a "solvation shell." This solvated ion migrates toward the cathode via the porous polymeric separator with the help of the electrolyte [**78**]. Before the ion can intercalate (insert itself) into the metal oxide cathode's lattice structure, it must de solvate, or shed its solvent shell, once it reaches the cathode. An applied electrical current reverses this precise physical process during charging. In the interactive graphic below, examine this internal design and the actual connections between the electrodes, separator, and electrolyte fluid [**79**].

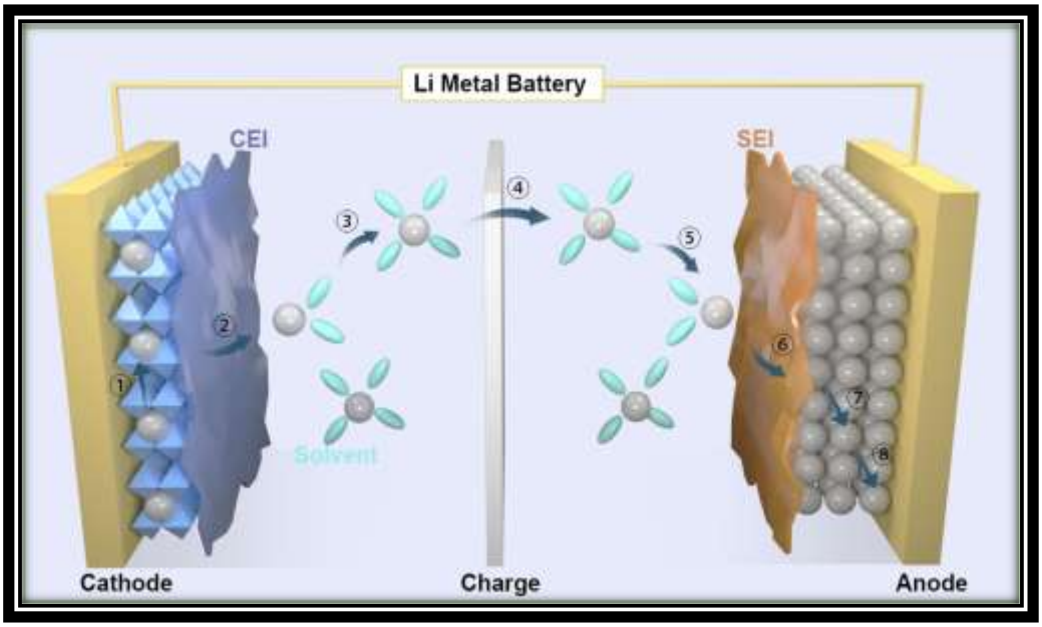


Figure 3: Schematic diagram of the transport steps of Li^+ ions from cathode to anode

Source: https://www.oaepublish.com/articles/cs.2024.66

5. SOLID STATE ELECTROLYTE:

The distinguishing feature of a solid-state battery is a solid-state electrolyte (SSE), which is a solid ionic conductor and electron-insulating substance. It can be used to replace liquid electrolytes, especially those present in lithium-ion batteries, in electrical energy storage applications [**80**]. Their primary benefits are complete safety, no problems with harmful organic solvent leaks, low flammability, non-volatility, mechanical and thermal stability, ease of processing, low self-discharge, higher attainable power density, and cyclability [**81**]. The property of lithium dendrite suppression in the presence of a solid-state electrolyte membrane, for instance, enables the use of a lithium metal anode in a practical device without the inherent restrictions of a liquid electrolyte [**82**]. The first step toward creating a lighter, thinner, and less expensive rechargeable battery is to replace the conventional low capacity graphite, which has a theoretical capacity of 372 mAh/g in its fully lithiated state of LiC_6, with a high-capacity and low reduction potential anode, such as lithium, which has a specific capacity of 3860 mAh/g and a reduction potential of -3.04V vs standard hydrogen electrode [**83**].This enables volumetric and gravimetric energy densities high enough for an electric car to go 500 miles on a single charge, the transition of SSEs from academic study to large-scale production is still hampered by a number of issues, chief among them being their weak ionic conductivity in comparison to their liquid counterparts, despite these encouraging benefits [**84,85**].

5.1. HISTORY OF SOLID-STATE ELECTROLYTE

The initial inorganic solid-state electrolytes were found by Michael Faraday in the 1800s, which included silver sulphide (Ag_2S) and lead (II) fluoride (PbF_2) [**86**]. The first polymer capable of facilitating in the solid state was PEO, identified in the 1970s by V. Wright. The significance of this discovery was acknowledged in the early 1980s [**87**]. Nonetheless, there are still basic issues that have not been addressed, which are essential for comprehending the function of all-solid batteries, particularly regarding electrochemical interfaces. In the last few years, the demand for enhanced safety and performance in comparison to current Li-ion technologies has rendered solid-state batteries increasingly attractive, and they are now viewed as a promising solution to fulfil the requirements for long-range battery electric vehicles soon [**88**].

In March 2020, the Samsung Advanced Institute of Technology (SAIT) released findings regarding an all-solid-state battery (ASSB) that incorporates an argyrodite-derived solid-state electrolyte. This innovation exhibited an energy density of 900 WhL^{-1} and maintained stable performance over more than 1000 cycles, marking a significant milestone as it approached the 1000 WhL^{-1} benchmark for the first time. The enhancement in electrode and electrolyte contact was accomplished through the technique of warm isostatic pressing **[89]**.

The research on Semi-Solid Transition (2024–2026) focus on Hybrid gel/polymer solid-state cells (300 – 360 Wh/kg) have entered commercial production for commercial electric vehicles and eVTOL aircraft, and Full sulphide/halide-based all-solid-state batteries (400 – 500 Wh/kg) are currently undergoing pilot-line validation and vehicle integration tests, with initial low-volume automotive commercialization planned for 2027.

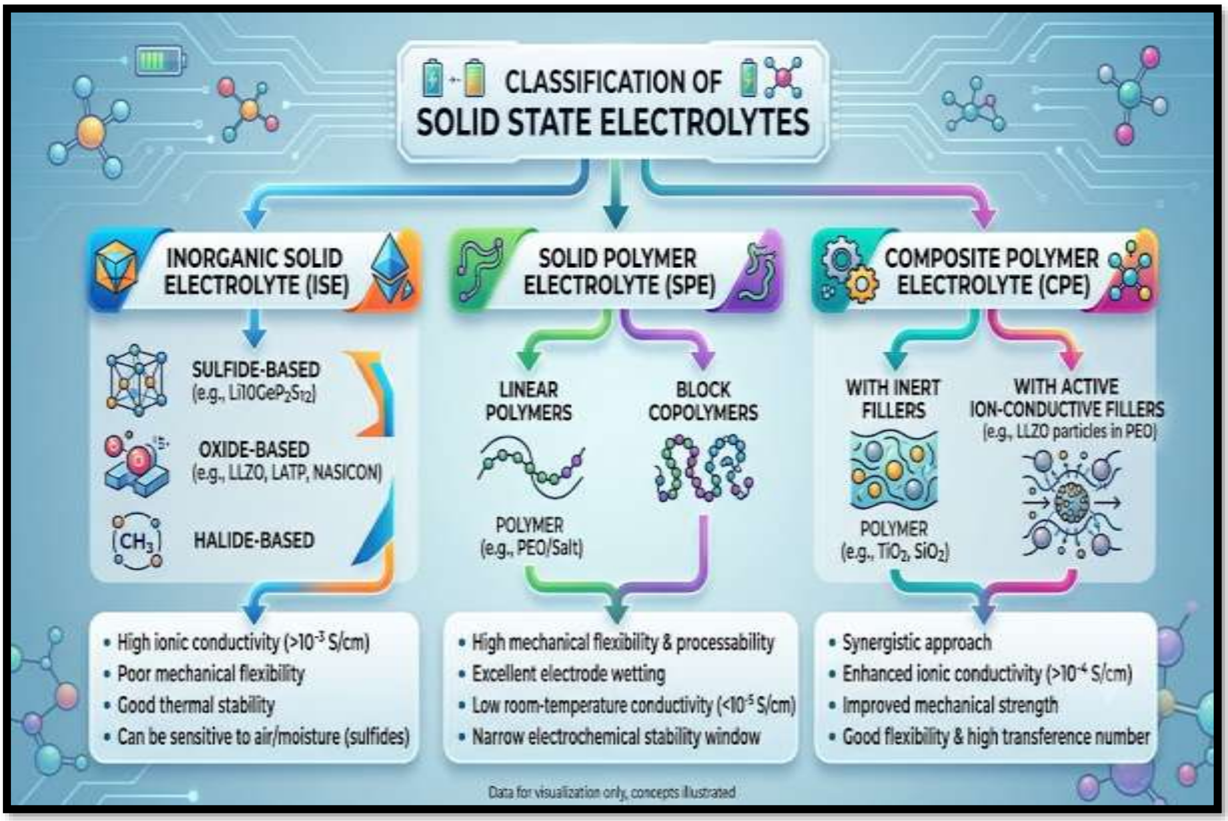
6.CLASSIFICATION OF SOLID-STATE ELECTROLYTE:

SSEs are categorised as all-solid-state electrolytes and quasi-solid-state electrolytes (QSSE), and they play the same function as conventional liquid electrolytes. Additionally, there are three types of all-solid-state electrolytes: composite polymer electrolyte (CPE), solid polymer electrolyte (SPE), and inorganic solid electrolyte (ISE). Conversely, a QSSE, also known as gel polymer electrolyte (GPE), is a freestanding membrane with a specific amount of liquid immobilised within the solid matrix. Although the terms SPE and GPE are sometimes used interchangeably, they have quite different ionic conduction mechanisms: GPEs conducts ions primarily in the solvent or plasticiser, whereas SPEs conduct ions by interaction with the substitutional groups of the polymer chains **[90,91]**.

6.1. Inorganic Solid-State Electrolyte:

Ions are conducted by diffusion through the solid lattice in inorganic solid electrolytes (ISEs), a class of all-solid-state electrolytes made of inorganic materials in either crystalline or glassy form. Significant benefits of these electrolytes include a high mechanical modulus (GPa scale), a high cation-transfer number, and relatively high ionic conductivity (on the order of 10^{-3}-10^{-4} S/cm at ambient temperature) **[92,93]**.

Single-phase materials are the norm for traditional ISEs. Because of their exceptional mechanical durability and chemical stability, oxide-based conductors are extensively researched [94]. Oxide conductors such NASICON-type LTP, LATP and LAGP, garnet-type LLZO, and perovskite-type LLTO are examples of common crystalline structure families. LGPS-type $Li_{10}GeP_2S_{12}$ and argyrodite-like Li_6PS_5X are examples of sulphide-based ISEs. These materials can provide strong ionic conductivities and very soft mechanical behaviour, which promotes interfacial contact. $Li_{10}GeP_2S_{12}$, a lithium superionic conductor with room-temperature lithium-ion conductivity comparable to liquid electrolytes, was described by Kamaya et al. in 2011. Lithium nitrides, lithium hydrides, lithium phosphidotrielates, and phosphidotetrelates are further inorganic groups **[95,96]**.



Nevertheless, single-phase ISEs still have a lot of difficulties despite these advantages. Despite their mechanical strength, oxide ceramics frequently require high sintering or stack pressure to obtain good contact, are brittle, and produce significant interfacial resistance at the electrode/electrolyte interface. However, despite having strong ionic conductivity, sulphide and halide materials may have restricted electrochemical windows, mechanical softness, and chemical instability (such as moisture sensitivity or an unwanted reaction with Li metal) **[97,98,99]**.

6.2. Solid polymer electrolyte (SPE):

Solvent-free salt solutions in polymer hosts that allow ion transport via polymer chains are known as solid polymer electrolytes (SPEs). SPEs have greater flexibility and plasticity than inorganic solid electrolytes (ISEs) and are simpler to manufacture, usually through scalable solution casting **[100]**. During battery operation, these characteristics guarantee interface flexibility, stability, and resistance to volumetric fluctuations [101]. Strong lithium-salt dissolution, a low glass transition temperature (Tg), low crystallinity, low temperature sensitivity, mechanical stability, and compatibility with standard electrodes are all necessary for an excellent SPE **[102]**. However, quick charging is limited by SPEs' weaker ionic conductivity compared to ISEs. For instance, SPEs based on poly (ethylene oxide) (PEO) enable ion hopping through chain segmental motion through ether group complexation; nevertheless, their ionic conductivity is suppressed to about 10^{-5} " S/cm" because to high room-temperature crystallinity **[103]**.

Structural changes like copolymerisation, cross-linking, interpenetration, and blending are used to get around these restrictions and raise the amorphous-to-crystalline ratio. Salt dissolving is greatly increased by adding polar functional groups, such as ethers, carbonyls, or nitriles [**104**]. Polycarbonates, polyesters, polynitriles (like PAN), polyalcohol's (like PVA), polyamines (like PEI), polysiloxanes (like PDMS), and fluoropolymers (like PVDF, PVDF-HFP) are notable synthetic substitutes for polyether's. Furthermore, because of their strong salt-complexation capacity and environmental friendliness, biopolymers like cellulose, lignin, and chitosan are showing promise as standalone or blended matrix materials [**105**].

6.3. Composite polymer electrolytes:

The limitations of conventional inorganic solid electrolytes (ISEs), such as garnet-based (LLZO) and sulphide-based (LGPS) materials, which frequently show poor mechanical compatibility with lithium electrodes and high interfacial resistance, are potentially addressed by composite polymer electrolytes (CPEs) [**106**]. CPEs, sometimes known as composite solid electrolytes (CSEs), combine the flexibility and improved electrode compatibility of polymers with the high ionic conductivity of inorganic phases by incorporating tiny inorganic particles into a polymeric matrix [**107**].

There are two types of inorganic fillers used in the polymer matrix: inert and active. The main purpose of inert fillers like Al2O3, TiO2, and SiO2 is to increase mechanical strength and decrease the crystallinity of the polymer matrix, which inhibits the growth of lithium dendrites [108]. For example, research has shown that adding SiO2 to a PEO-based electrolyte greatly improves its mechanical strength and thermal stability, resulting in longer cycle life in lithium symmetric cells [109]. In addition to strengthening the polymer matrix, active fillers—such as fast-ion conductors like LLZO, LLTO, and LATP—also offer extra channels for lithium-ion conduction, raising the electrolyte's total ionic conductivity [110].

The application of electrospun LATP nanosheets in a PVDF matrix, which created continuous ion transport channels and produced a high ionic conductivity of 6.15×10^{-4} S/cm at room temperature, is a noteworthy example [111]. In order to establish continuous Li+ transport channels within PEO-based CPEs, structural design techniques such building three-dimensional fibre networks with materials like PAN/LLZTO have been used, further improving ionic conductivity and mechanical qualities' successfully reduce interfacial resistance and contribute to more stable cycle performance in all-solid-state lithium metal batteries by providing greater processability and addressing the rigid interfacial contact problems present in pure ISEs[**112,113,114**].

7.ROLE OF SOLID STATE ELECTROLYTE IN LUTHIUM IONS BATTERIES

The liquid electrolyte in traditional lithium-ion (Li-ion) batteries only serves as an ion-transporting medium between two electrodes. The solid-state electrolyte (SSE) of next-generation All-Solid-State Batteries (ASSBs) transforms from a passive liquid layer into the main structural, chemical, and mechanical framework of the cell[**115**]. A conceptual paradigm shift is reflected in recent literature, which is emphasised by thorough reviews and material science roadmaps (like the 2026 Roadmap on Next-Generation Solid Electrolytes for Battery Applications): SSEs are moving from passive ionic conductors to multifunctional, active design elements in energy storage systems[**116**].

7.1.Dual function: superionic conductor and seprator:

Liquid solvents and porous polymeric separators (like Celgard) are no longer necessary thanks to the SSE. To avoid self-discharge, it must act as an electronic insulator $\sigma_e < 10^{-10}$ S/cm< 10^{-10}S/cm) and retain high ionic conductivity ($\sigma_{Li^+} > 10^{-3}$S/cm).Enabling Pure Lithium-Metal Anodes Runaway Solid Electrolyte Interphase (SEI) development and dendrites are caused by the continual breakdown of liquid electrolytes against metallic lithium. Unlocking pure Li-metal anodes (3,860mAh/g theoretical capacity compared to graphite's 372mAh/g), solid electrolytes offer a stiff matrix that can suppress dendrite penetration[**117**]. High-voltage cathode chemistries (such high-Ni NMC or cobalt-free manganese spinels) can be used without electrolyte oxidation because many solid electrolytes are thermodynamically or kinetically stable above 4.5V to 5.0V vs. Li /Li^+[118].

7.2.Entropy & Compositionally Complex Electrolytes:

Moving beyond traditional single-phase ceramics (like garnet LLZO or sulfide LGPS), recent studies leverage high-entropy solid electrolytes (HESEs)[**119**]. By incorporating multiple cation or anion species into a single lattice phase, researchers introduce lattice distortion and expanded migration pathways Increased compositional entropy lowers activation energy barriers for Li^+ site-to-site hopping.and Enables ionic conductivities exceeding 10^{-2}S/cm at room temperature while preserving mechanical ductility[**120**].

Despite having high ionic conductivities, sulphide electrolytes (such as argyrodites Li_6PS_5Cl) break down at voltages 3.8V and release hazardous H_2S gas when exposed to air. Halide-based solid electrolytes, such as Li_3InC_6, Li_3YCl_6, and Li_2ZrCl_6, have received a lot of attention in recent papers[**121**]. High Oxidation Stability: Direct contact with uncoated high-voltage nickel-rich cathodes is made possible by its chemical stability up to 4.8V[**122**].Deformability During manufacturing, cold pressing is possible without the need for high-temperature sintering processes because to highly ductile mechanics.

Using sophisticated operando techniques (such Solid-State NMR, Synchrotron X-ray Tomography, and Cryo-TEM) to visualise the solid-solid interface during operation is a key focus of contemporary literature. Recent research shows that localised electrical conductivity and stress accumulation cause lithium dendrites to spread along grain boundaries in solid ceramics.Interfacial Buffering Solutions: To account for volume variations during lithium plating and stripping, researchers employ atomic layer deposition (ALD) and thin polymer/gel interlayer coatings (creating hybrid/composite interfaces)[**123,124**].

7.3.Lithium Plating & Grain Boundary Suppression:

Dendrites are created along ceramic grain boundaries by mechanical stress concentration and electrical leakage rather than chemical breakdown as in liquids. Uniform lithium nucleation can be controlled by introducing thin buffer interlayers at the anode interface, such as silver-carbon (Ag-C) or alloy-forming metals like In, Sn, or Zn[**125**].

7.4.Space-Charge Layer & Cathode Degradation:

A high-resistance space-charge layer is produced by drawing Li^+ ions away from sulphide SSE contacts using high-voltage oxide cathodes (NMC/LCO). To stop chemo-mechanical breakdown, advanced structures use atomic layer deposition (ALD) coatings, such as borates or $LiNbO_3$[**126**] .

8.ADVANTAGE OF SOLID STATE ELECTROLYTE

8.1.Improved energy density:

Compared to conventional lithium-ion batteries, solid-state batteries have the potential for far higher energy densities. The usage of lithium metal anodes, which have a significantly higher charge capacity than the graphite anodes found in lithium-ion batteries, is mostly to blame for this. Solid-state battery energy densities can surpass 350 Wh/kg, although lithium-ion energy densities are often less than 300 Wh/kg at the cell level. Applications like electric vehicles that need batteries that are more compact and long-lasting would particularly benefit from this increase in energy density[**127,128**].

8.2.Increase of safety and thermal stability:

The enhanced safety profile of solid-state batteries is one of their main advantages. One of the main causes of battery fires, thermal runaway, is significantly decreased by solid electrolytes. Solid-state batteries offer a far reduced fire danger and require fewer safety mechanisms because the majority of solid electrolytes are nonflammable. This can further boost energy density at the cell pack level.According to studies, only 20–30% of the heat produced during thermal runaway is seen in conventional batteries using liquid electrolytes[**129,130**].

8.3.Expanded temperature and voltage operating ranges:

For high performance applications, a wider range of operating temperatures and voltages is made possible by solid electrolytes.While traditional SSBs typically only function between -20 and 60 °C, SSBs can function at temperatures exceeding 60 °C.High-voltage cathode chemistries including lithium nickel manganese oxide, lithium nickel phosphate, and lithium cobalt phosphate are also supported by solid state batteries. This makes it possible for voltages to surpass 5 V (compared to a Li/Li+ reference electrode), whereas conventional cathode chemistries in lithium-ion batteries can only surpass 4.5 V (compared to a Li/Li+ reference electrode)[**131**].

8.4.Faster charging and improved space efficiency:

Compared to lithium-ion batteries, the combination of the solid electrolyte and lithium metal anode allows for faster ion transfer, which can shorten charging periods. Additionally, it is possible to add bipolar stacking of cells, which enables smaller cells and more compact battery packs.Improved overall energy efficiency and design flexibility for a range of applications are made possible by this[**132**].

8.5.Longer Cycle Life & Broad Operating Rang:

Minimal Side Reactions: Over time, liquid batteries usually deteriorate due to parasitic chemical reactions like transition metal dissolution from the cathode, which are lessened by solid electrolytes.Extreme Temperature Tolerance: In cold and hot conditions, where liquid electrolytes either freeze, lose conductivity, or deteriorate quickly, SSEs function dependably[**133**].

9.LIMITATION OF SOLID STATE CHALLENGE

9.1.Cost of thin-film:

The production of thin-film solid-state batteries is costly and involves costly vacuum deposition equipment and manufacturing techniques that are anticipated to be challenging to scale. Consequently, thin-film solid-state battery costs become unaffordable for consumer-based applications. A 20 Ah solid-state battery cell was expected to cost US $100,000 in 2012 based on then-current technology, and 800–1,000 of these cells would be needed for a high-range electric vehicle.Similarly, the use of thin-film solid-state batteries in other applications, including cellphones, has been hindered by cost[**134**].

9.2Temperature and pressure sensitivity:

Operations at low temperatures could be difficult.In the past, solid-state batteries have performed poorly.High pressure is necessary for solid-state batteries with ceramic electrolytes to keep the electrodes in contact. Mechanical stress can cause solid-state batteries with ceramic separators to fail.Using copolymerised novel materials for electrolyte, A Japanese team (Kyoto, Tottori, Sumitomo) solved low-temperature, high-pressure, and mechanical stress issues in solid-state batteries by using copolymerized electrolytes, achieving 230 Wh/kg capacity without pressure. Osaka Metropolitan University researchers stabilized high-temperature α-Li_3PS_4 phase at room temperature by fast-heating and crystallizing Li_3PS_4 glass to enhance battery operation.

9.3. Interfacial resistance:

For all-solid-state batteries, high interfacial resistance between a cathode and solid electrolyte has long been an issue.Modern equipment made especially for solid-state batteries, like warm isostatic pressing, applies a nearly uniform pressure throughout the solid electrolyte, resulting in more homogeneous densification and, consequently, reduced bulk and grain boundary resistivity[**135**]. In contrast, traditional densification techniques used in Li-ion battery production, such as hot-rolling and uniaxial pressing, produce a non-uniform closure of porosity in the solid electrolyte[**136**].

9.4.Resource and energy consumption issues:

Significant amounts of energy and natural resources are used in the extraction, processing, and manufacture of raw materials. The production process uses a lot of energy, which raises carbon emissions, and the mining and processing of new elements might harm the environment[**137**].

9.5.Recycling challenges:

Solid-state battery recycling and disposal present difficulties. They have intricate internal structures made up of numerous metals and compounds. Recycling technology and procedures are expensive and inexperienced, and improper recycling can contaminate the environment[**138**].

9.6.Low ionic conductivity:

Solid electrolytes have weaker ionic conductivity than liquid electrolytes due to the strong ion contact and high migration energy barriers, which causes slow charging and discharging rates and quick capacity fading[**139**].

10.APPLICATION OF SOLID STATE ELECTROLYTE

10.1.Next generation electric vehicles(Ev):

SEs allow pure lithium metal to be used in place of traditional graphite anodes. Longer driving ranges on a single charge are made possible by this increase in volumetric and gravimetric energy density (400 Wh/kg)[**140**].

10.2. Fast charging ans safety:

Non-flammable inorganic SSEs (such as Garnet-type LLZO and NASICON-type LTP) can tolerate high temperatures, reducing the risk of thermal runaway during high-power fast-charging cycles, in contrast to liquid electrolytes[**141**].

10.3. High capicity lithium sulphur(li-S) batteries:

The "polysulphide shuttle effect," in which intermediate lithium polysulfides dissolve and migrate, causes liquid electrolytes to rapidly lose capacity. By acting as a physical barrier, SSEs unlock the high theoretical capacity of sulphur (1675 mAh/g) and lock polysulfides at the cathode[**142].**

10.4. Metal Air batteries:

SSEs address important degradation mechanisms in open-system metal-air designs by shielding the lithium anode from moisture and ambient CO2 contamination while preserving ionic transport[**143**].

10.5.Sodium ion and potassium batteries:

In order to lessen dependency on lithium resources, solid-state sodium electrolytes (alumina, Na-NASICON) are frequently used in solid-state sodium batteries for large-scale grid energy storage[**144**].

10.6.Wearable and implantable medical devices:

Solid polymer and ceramic electrolytes offer the complete leak-proof safety and biocompatibility needed for devices like pacemakers, smart contact lenses, and biometric sensors.

10.7.Aerospace and Defense:

Batteries used in satellite and space exploration equipment must operate in a wide range of temperatures (sub-zero to>100°C) without freezing or vaporizingconditions in which liquid electrolytes break down[**145**].

11. ENVIROMENT AND ECONOMIC CONSIDERATIONS:

11.1. Enviroment Considerations:

11.1.1. Mining and Extraction:

Large volumes of water and hazardous chemicals are needed to extract raw materials like nickel, cobalt, and lithium, which depletes freshwater supplies, contaminates soil, and destroys habitats[**146].**

11.1.2. Operational Efficiency:

Battrixx emphasizes that modern battery technology outperforms conventional fossil fuels in terms of energy conversion efficiency. These battery systems eliminate waste heat, significantly reduce overall energy consumption, and successfully reduce harmful greenhouse gas emissions to promote the sustainable energy transition by turning a higher percentage of stored energy into usable electricity[**147**].

11.1.3. Recycling Benefit:

Compared to conventional mining, recovering essential components from expended batteries offers significant environmental advantages. Battery recycling significantly lessens resource depletion and lifecycle carbon footprints by producing up to 80% fewer greenhouse gas emissions and using 80% less water[**148**].

11.1.4. Carbon Footprint:

Depending largely on the regional grid mix where the gigafactory runs (e.g., coal-heavy vs. hydro-heavy grid power), the production of a LIB produces around 60"−150 kg CO_2/ kWh of battery capacity[**149**].

11.1.5. Landfill Risks:

Improperly disposed lithium-ion batteries pose severe thermal runaway fire risks and environmental hazards. They can leach toxic transition metals like cobalt, nickel, and manganese, along with hazardous fluorinated electrolytes and hydrofluoric acid derivatives, directly into soil and groundwater systems [**150**].

11.1.6. Hydrometallurgy:

Chemical leaching effectively extracts high-purity lithium, cobalt, and nickel, needing considerably less energy than traditional pyrometallurgy. Nonetheless, this hydrometallurgical method produces acidic and basic chemical wastewater, requiring strict environmental treatment measures to make the effluent safe for release [**151**].

11.2. Economic Considerations

11.2.1. Production Costs:

The most resource-intensive stage of production is the synthesis of cathode active materials, which accounts for more than 45% of the costs and environmental effects associated with battery production. Therefore, reducing economic and ecological footprints requires streamlining precursor synthesis and raw material processing[**152**].

11.2.2. Supply Chain Volatility:

Geopolitical unrest and changes in regional production are the main causes of battery metal supply chain volatility. Important areas like Indonesia and Central Africa have a significant impact on the cost of raw materials, leading to significant market swings and difficulties in strategic sourcing[**153**].

11.2.3. Recycling and Circular Economy:

Recovering essential minerals opens up a multibillion-dollar business that is expanding quickly. However, increasing collection rates, streamlining reverse logistics, and creating favorable regulatory policy incentives are critical to scaling effective circular systems like direct recycling[**154**].

11.2.4. Geopolitical & Geographic Concentration:

There is a lot of regional centralization in the LIB supply chain. Although extraction takes place all over the world (such as in Chile, Australia, and the Democratic Republic of the Congo), China is a major hub for cell/component manufacture and raw chemical refinement. Risks of supply bottlenecks and exposure to trade barriers result from this[**155**].

11.2.5.Commodity Price Fluctuation:

Pack margins are directly impacted by sharp price fluctuations in lithium, nickel, and cobalt, which forces manufacturers to switch to less expensive, cobalt-free chemistries like lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP)[**156**].

11.2.6.Second-Life Applications:

Used EV batteries maintaining 70–80% capacity can be profitably recycled into stationary Energy Storage Systems (ESS). They efficiently assist in balancing grid loads and incorporate renewable energy prior to ultimately being recycled as materials [**157**].

11.2.7. Supply Chain Resiliency:

Rrecycling used batteries provides a dependable local secondary source of essential minerals such as lithium, cobalt, and nickel. This greatly decreases dependence on imported raw minerals, enhances supply chain stability, and successfully protects national economies from unpredictable global price fluctuations [**158**].

CONCLUSION

The evolution of energy storage from standard lithium-ion batteries built on the foundational working principles of ion intercalation between positive and negative electrodes has reached a monumental juncture. While conventional lithium-ion battery technology has powered modern electronics and early electric vehicles, its fundamental reliance on volatile organic liquid electrolytes introduces severe safety hazards, persistent capacity degradation, and strict energy density ceilings. Solid-state electrolytes have emerged as the paramount technical solution to these historical chemical vulnerabilities. Evolving over decades of material science breakthroughs into distinct structural classifications including inorganic oxide or sulfide ceramics, solid polymers, and advanced composite materials, solid-state electrolytes fundamentally redefine internal battery dynamics. By acting as both an efficient ion conductor and a robust physical separator, their core role is to eliminate hazardous leakage, suppress destructive lithium dendrite growth, and enable the seamless integration of pure lithium-metal anodes. This architectural leap yields unmatched operational advantages: exceptionally high gravimetric and volumetric energy densities, rapid charging tolerance, and superior non-flammable thermal safety. However, widespread commercial deployment must overcome critical limitations and implementation challenges, namely severe solid-solid interfacial resistance, limited ambient ionic conductivity in specific polymer matrices, mechanical fracturing, and expensive manufacturing scaling. Successfully resolving these interdisciplinary hurdles unlocks transformative applications across next-generation long-range electric vehicles, flexible wearable electronics, implantable medical devices, and extreme-environment aerospace systems. Furthermore, evaluating this technological paradigm through rigorous environmental and economic lenses indicates that despite energy-intensive raw material mining and substantial initial gigafactory capital expenditures, solid-state configurations optimize long-term lifecycle sustainability. Extended calendar lifespans eliminated toxic liquid hazards, and high-yield hydrometallurgical recycling pathways offset upstream ecological footprints while lowering the ultimate total cost of system ownership. In summary, solid-state electrolytes bridge legacy liquid limitations with next-generation performance, establishing a safer, highly efficient, and economically viable electrochemical baseline to power future global electrification infrastructure worldwide.

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