

Liquid Crystal as Solid Electrolytes: Selected Developments and Perspectives

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Abstract: The liquid crystalline state arises from orientation-dependent, non-covalent interactions among molecules in condensed phases, producing materials that combine structural order with molecular mobility. Because this ordered arrangement depends on a delicate balance of intermolecular forces, liquid crystals (LCs) are highly responsive to external stimuli, making them attractive for sensing and electrochemical applications. This review critically examines recent advances in liquid crystal-based solid electrolytes, with emphasis on materials design strategies, ionic transport mechanisms, and electrochemical performance. The discussion is organized into key thematic sections covering (i) fundamental intermolecular interactions governing liquid crystalline behavior, (ii) classes of ionic liquid-crystalline systems, including zwitterionic and mesoionic mesogens, and (iii) liquid crystalline materials composed of organic cations paired with organic or inorganic anions interacting through electrostatic and other non-covalent forces. Representative studies from recent literature are analyzed to highlight structure–property relationships and performance trends in solid-state devices such as lithium batteries, fuel cells, and dye-sensitized solar cells. By integrating material design principles with functional performance analysis, this review provides a focused perspective on the potential and limitations of liquid crystalline solid electrolytes for next-generation all-solid-state technologies.

Keywords: liquid crystals; solid electrolyte; batteries; fuel cells; solar cells.

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1. Introduction

Liquid crystals (LCs) are intermediate phases between crystalline solids and isotropic liquids, characterized by long-range orientational order and, in some cases, partial positional organization [1]. Unlike conventional liquids, this partial ordering enables anisotropic physical properties while retaining molecular mobility [2]. In contrast, isotropic liquids lack both orientational and positional order [3]. Ionic liquid crystals extend this concept by incorporating charged species, cations, and anions into the mesogenic framework [4]. The presence of Coulombic interactions significantly alters phase behavior, conductivity, and thermal response compared with neutral LCs [5]. Although first reported in 1938, ILC research has experienced renewed growth due to increasing interest in ionic liquids and solid-state electrochemical systems [6].

LC-based materials are now actively explored in batteries, fuel cells, and other energy storage technologies because their ordered yet dynamic structures can support directional ion

transport [7]. Replacing conventional liquid electrolytes with LC-based systems can enhance safety and widen operational temperature ranges [8]. Their hybrid character, combining mesophase organization with solid-like mechanical networks, forms the conceptual basis of LC-derived solid electrolytes [9]. These systems inherit structural anisotropy from LCs while gaining dimensional stability from the supporting matrix [10]. Importantly, nanoscale self-assembly governs ion transport behavior. Ionic segregation may generate percolated nanochannels that facilitate anisotropic conduction, while structural fluctuations can influence plasticization and segmental mobility [11,12]. Such organized architectures substantially broaden potential applications, ranging from electrochemical devices to thermally responsive diagnostic systems that rely on intrinsic LC anisotropy [13].

1.1. Structure-property relationships and ionic conduction.

The anisotropy of liquid crystals originates from the parallel alignment of elongated mesogenic molecules. This alignment produces direction-dependent dielectric, thermal, and electrical properties. For electrolyte applications, anisotropic ionic conductivity is especially important.

Rigid aromatic cores, polar or ionic terminal groups, and flexible alkyl chains make up typical mesogens, each of which contributes unique functional characteristics. The polar or ionic terminal groups strengthen dipolar contacts and enable ion dissociation along the molecular axis, while the stiff aromatic cores encourage directional stacking and aid in stabilizing ordered domains. Furthermore, the flexible alkyl chains promote nanosegregation between ionic and non-ionic regions and enhance mesophase development.

The relationship between molecular architecture and mesophase structure directly determines nanochannel formation and ion mobility. Conductivity is frequently higher along the director axis due to preferential ion migration pathways. Therefore, rational molecular design is essential for optimizing LC electrolytes for electrochemical performance.

1.2. Symmetry and mesophase organization.

Symmetry plays a defining role in determining transport dimensionality in LC electrolytes.

Anisotropic conduction is made possible by nematic phases' orientational order, although they lack fixed nanochannels for directed transport. Smectic phases, on the other hand, produce layered structures that enable more ordered ion transport by forming two-dimensional conduction planes. In contrast, columnar phases are very useful for directional ionic transport because they form into one-dimensional cylindrical structures that can act as continuous ion-conducting channels.

In ionic systems, microphase separation between charged and neutral segments often produces ordered ionic domains. The geometry and connectivity of these domains govern ionic percolation and overall conductivity. Thus, symmetry considerations are directly linked to electrolyte efficiency rather than being purely structural descriptors.

2. Mesogenic Molecules and Ionic Self-assembly

Mesogenic molecules capable of forming LC phases encompass diverse chemical classes. In electrolyte-oriented systems, molecular design prioritizes ionic aggregation and

nanostructured segregation. Electrostatic interactions, hydrogen bonding, and van der Waals forces collectively drive self-assembly.

Researchers can customize the material's ionic domain spacing, thermal stability window, conductivity anisotropy, and mechanical resilience to produce desired structural and electrochemical properties by altering cation–anion combinations, spacer length, and side-chain architecture.

Blending strategies and polymer-stabilized networks further enhance dimensional stability while preserving organized ion-conducting pathways. Such tunability allows rapid adaptation of LC electrolytes for various electrochemical devices.

3. Structural Characterization and Transport Analysis

Diffraction methods are still essential for determining nanoscale ordering and mesophase structures. The shape of conduction channels is intimately correlated with layer spacing and columnar packing, which may be determined via X-ray diffraction. A deeper understanding of ion transport pathways has been made possible by recent developments in characterization techniques. While solid-state NMR spectroscopy aids in the study of molecular dynamics, small-angle X-ray scattering (SAXS) is frequently utilized for nanoscale domain research. Neutron scattering is useful for examining the distribution of ions within the material, and dielectric spectroscopy provides information on frequency-dependent conductivity. When combined, these methods allow for a quantifiable relationship between ionic mobility and mesophase organization.

3.1. Phase transitions and conductivity.

LC systems undergo transitions upon changes in temperature, pressure, or composition. Such transitions directly impact ionic mobility. Typically, moving from a crystalline phase to a mesophase increases conductivity because enhanced molecular motion improves ion transport, while the loss of ordered nanochannels in the isotropic phase may reduce directional transport. Control of phase transition temperatures is therefore essential for stable device operation.

3.2. Magnetic, electric properties.

Molecular dipoles and dielectric anisotropy influence ion dissociation and migration. Because molecular properties can be averaged over the mesophase orientational distribution, macroscopic dielectric permittivity and conductivity can be quantitatively related to microscopic parameters. Electric or magnetic fields may also reorient domains, potentially enabling controlled alignment of ion-conducting pathways.

3.3. Elastic properties.

Elastic constants and viscosity arise from intermolecular interactions and collective ordering. These properties affect defect formation, domain stability, and mechanical durability. In LC electrolytes, a balance must be achieved between structural rigidity and ionic mobility, often through cross-linked or polymer-stabilized networks.

3.4. Optical properties.

Optical anisotropy, including birefringence, reflects the internal orientational order of LC mesophases. Although primarily associated with photonic applications, optical measurements also provide indirect evaluation of structural uniformity and domain organization in electrolyte systems. Light scattering from nanoscale fluctuations offers additional information about heterogeneity and structural transitions.

4. Impact of Molecular Arrangement on Electrochemical Properties

The electrochemical performance of liquid crystalline (LC) electrolytes is governed by mesoscale molecular organization rather than chemical composition alone. In anisotropic LC phases, mesogens adopt long-range orientational order, creating spatially correlated domains that dictate the dimensionality of ion transport, pathway continuity, and activation energy barriers. Ionic conduction in LC systems proceeds through percolated nanochannels formed by microphase segregation between ionic and non-ionic regions. The degree of orientational order directly affects transport anisotropy: higher order parameters reduce pathway tortuosity and lower the energetic penalty for ion hopping. Consequently, aligned mesophases show reduced bulk resistance and higher ionic conductivity than isotropic or poorly organized states.

Mechanistically, ion migration occurs through a combination of vehicle transport (ion-solvent complex diffusion) and hopping between coordination sites. Structured LC domains decrease free-energy barriers by providing periodic coordination environments and minimizing structural fluctuations that disrupt conduction pathways. This results in improved charge-discharge kinetics in lithium metal batteries and supercapacitors. External-field alignment (electric or magnetic) enhances macroscopic mesophase coherence, increasing long-range connectivity of ionic channels. Field-induced ordering improves directional conductivity and suppresses resistive grain boundaries. Therefore, molecular alignment is not merely structural but directly governs electrochemical efficiency and rate capability [14].

5. Constituents of Liquid Crystal Electrolytes

Liquid crystal electrolytes are architecturally engineered systems in which each component contributes to ion transport and mechanical integrity. Mesogenic frameworks provide anisotropic structural order. Their self-assembly into lamellar, columnar, or bicontinuous morphologies determines the dimensionality of conduction. Rigid cores ensure structural persistence, while flexible segments tune mobility. Ionic liquids (ILs) increase charge carrier concentration and facilitate salt dissociation. Their ionic character promotes the formation of conductive domains while maintaining low volatility and wide electrochemical windows. Metal salts (e.g., lithium salts) introduce mobile ions whose mobility depends on the solvation environment and domain connectivity. Additives, including plasticizers or compatibilizers, regulate free volume and segmental flexibility. By reducing excessive crystallinity and increasing dynamic heterogeneity, they promote ion mobility without collapsing ordered domains.

Optimal electrolyte design requires balancing structural order (for continuous pathways) with sufficient molecular mobility (for ion hopping). Excess rigidity suppresses dynamics, whereas excessive disorder disrupts percolation. Electrochemical performance therefore emerges from a cooperative interplay among structural anisotropy, ion concentration, and dynamic flexibility [15].

6. Roles of Ionic Liquids and Additives

Ionic liquids play a dual structural and functional role in LC electrolytes. Beyond serving as conductive media, ILs actively participate in mesophase organization through electrostatic and solvophobic interactions. Their incorporation promotes ionic nanochannel formation and enhances decoupling between ion motion and host-matrix relaxation. High ionic conductivity arises from increased ion dissociation and improved carrier mobility. Wide thermal stability and negligible vapor pressure contribute to operational safety in energy storage devices.

Additives modulate the balance between conductivity and mechanical robustness. Plasticizers increase free volume and reduce glass transition temperature, enabling faster segmental dynamics that facilitate ion transport. However, excessive plasticization may compromise electrochemical stability or dimensional integrity.

Thus, IL-mesogen-additive synergy must be optimized to maximize ionic mobility while preserving structural continuity and electrochemical durability [16].

7. Preparation Methods and Their Influence on Electrolyte Properties

The final morphology, crystallinity, and ionic route architecture of liquid crystal (LC) electrolytes are significantly influenced by processing conditions. Phase separation kinetics and domain size in solvent casting are regulated by solvent evaporation. While inadequate evaporation control can produce heterogeneous morphologies and break conduction networks, whereas uniform solvent removal eliminates structural flaws and promotes continuous mesophase alignment. A thermodynamically driven organization that takes place after solvent removal promotes the spontaneous creation of organized nematic, smectic, or columnar phases during phase separation and self-assembly. Anisotropic conductivity and the continuity of ion-conducting channels are significantly impacted by the resulting domain periodicity and alignment. The mechanical and structural characteristics of LC electrolytes are also influenced by polymerization and cross-linking. Mesophase structures inside mechanically resilient networks are stabilized by in situ polymerization, but careful optimization of the cross-link density is necessary. While insufficient cross-linking compromises the material's mechanical integrity, excessive cross-linking limits segmental motion and decreases ionic mobility. Electrolyte performance is also significantly impacted by thermal history. Crystallinity and free-volume distribution are determined by cooling rates: regulated cooling enhances structural order but may raise energy barriers for ion migration, whereas rapid quenching can trap disordered states with increased ionic mobility but reduced structural stability. As a result, morphological homogeneity, phase connectivity, and processing-induced anisotropy all affect ionic conductivity in addition to material composition [17].

8. Transitioning from Simple Electrolytes to Mesomorphic and Polymer Systems

The evolution from liquid electrolytes to polymer and mesomorphic systems reflects efforts to achieve decoupled ion transport where ionic mobility is partially independent of bulk polymer relaxation dynamics [18].

Polymer-LC hybrid architectures: Incorporating LC order into polymer matrices introduces structured ion pathways while retaining mechanical integrity. Triblock copolymers generate microphase-separated domains that balance rigidity and conduction [19].

Decoupled ion transport mechanism: In conventional polymer electrolytes, ion motion is strongly coupled to segmental α -relaxation. In mesomorphic systems, ordered domains provide alternative low-energy pathways, allowing ions to migrate through partially immobilized matrices [20]. Increased free volume, cooperative hopping sites, and anisotropic channels collectively enhance conductivity [21]. Side-chain LC polymers combine rigid backbones with mesogenic side groups that self-organize into conductive domains [22]. This design bridges polymer flexibility and mesophase order, improving both stability and ion mobility [23]. Glassy LC polymer electrolytes demonstrate that even systems with restricted global mobility can sustain ionic conduction via localized segmental motion and structured pathways [24].

8.1. Microstructure alignment and anisotropic transport.

Block copolymer systems reveal that conductivity strongly depends on microdomain orientation. Magnetic-field-assisted alignment produces long-range order, reducing tortuosity and increasing directional ion mobility [25]. These studies demonstrate that macroscopic alignment enhances anisotropic conductivity by establishing continuous, low-resistance channels [26].

8.2. Comparative ion pathways in different mesophases.

A schematic comparison clarifies transport dimensionality:

8.2.1. Lamellar (Smectic) phases.

Two-dimensional conduction confined within planar layers. High in-plane mobility but limited cross-layer transport [27].

8.2.2. Columnar phases.

One-dimensional cylindrical channels enable highly directional ion migration along column axes. Extremely anisotropic conductivity [28].

8.2.3. Bicontinuous cubic phases.

Three-dimensional interconnected networks providing isotropic yet continuous ionic pathways with minimal tortuosity [29].

Two-dimensional ionic LC assemblies further illustrate planar conduction architectures [30], whereas bicontinuous cubic phases provide fully interconnected proton-conductive networks [31]. Columnar and smectic nanostructures engineered through noncovalent design [32] or fluorinated stabilization yield efficient 1D [33] and 2D transport channels [34]. Electric-field-responsive columnar systems demonstrate dynamic modulation of lithium-ion mobility through structural polarization [35].

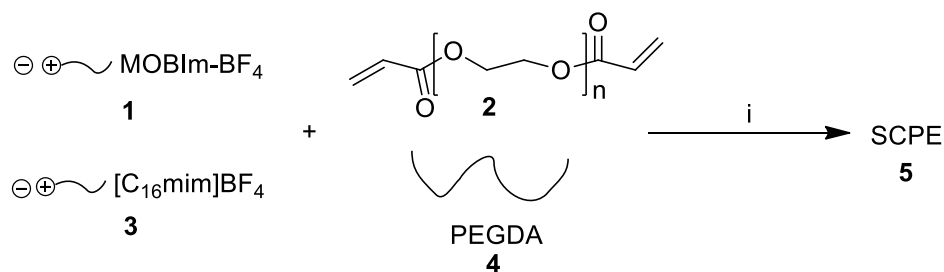
The transition from simple electrolytes to mesomorphic polymer systems therefore represents a shift from random diffusion to architecturally guided ion transport, enabling safer, higher-performance solid-state energy storage technologies.

9. Liquid Crystals as Solid Electrolytes: Multifaceted Roles in Energy Storage and Conversion Technologies

9.1. Lithium batteries.

Lithium batteries are expected to play a significant role in renewable energy storage systems and as power sources for sustainable vehicles, including hybrid and electric cars. However, scaling up lithium battery technology for diverse applications (Table 1) remains challenging because of cost, operating temperature range, safety, and the mechanical properties of electrolyte materials.

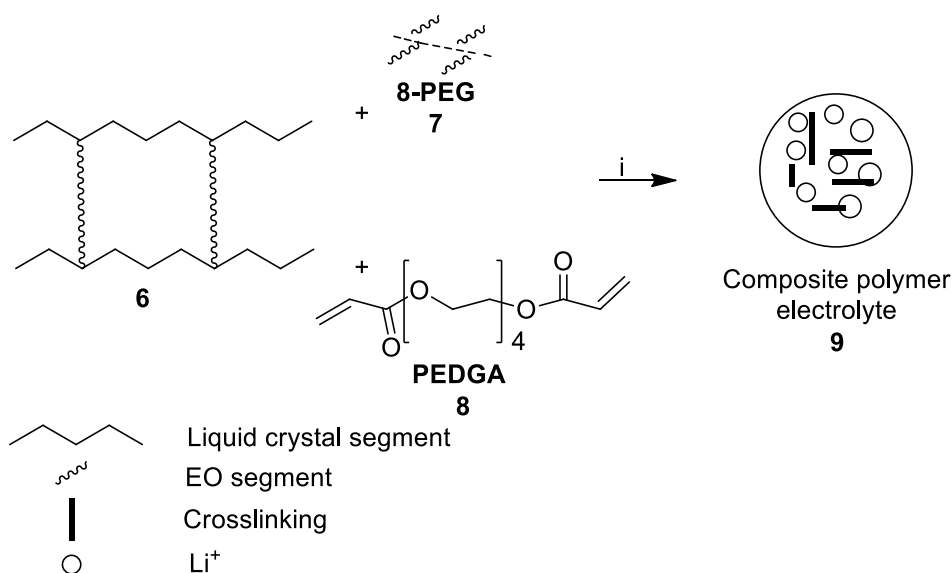
Ionic liquid crystals [1-hexadecyl-3-methyl tetrafluoroborate ($[C_{16}mim]BF_4$)] and polycationic liquids [1-(hexyl methacrylate)-3-butyrimidazolium tetrafluoroborate (PMOBI m)] were co-assembled using a flexible spacer to create a two-dimensional (2D) solid composite polymer electrolyte (SPE). (Figure 1) [36]. The ionic liquid crystals provide ion-conductive 2D pathways within cationic polymer ionic liquids, serving as effective media for lithium-ion transport. The PMPC 0.5 electrolyte (polyMOBI m - BF_4 /PEGDA/ $[C_{16}mim]BF_4$ = 3/1/0.5) demonstrated improved lithium-storage performance over a wide electrochemical window up to 4.2 V vs. Li^+/Li , with ionic conductivities of 7.14×10^{-5} and $2.17 \times 10^{-3} \text{ S cm}^{-1}$ at 25 and 95°C, respectively. These values were measured using a two-electrode blocking configuration with stainless steel electrodes. Its enhanced performance arises from thermal stability, non-flammability, and the formation of organized lamellar structures that facilitate Li-ion transport. In Li/SPE/LiFePO $_4$ coin cells, PMPC 0.5 exhibited a specific capacity of 136.7 mAh g $^{-1}$ in the first cycle and 118.9 mAh g $^{-1}$ after 40 cycles. While promising, further evaluation of scalability and long-term dendrite suppression is necessary for practical application.



Reagents and conditions: (i) UV induced

Figure 1. 2D solid composite polymer electrolyte tethered with $[C_{16}mim]BF_4$ and poly MOBI m - BF_4 .

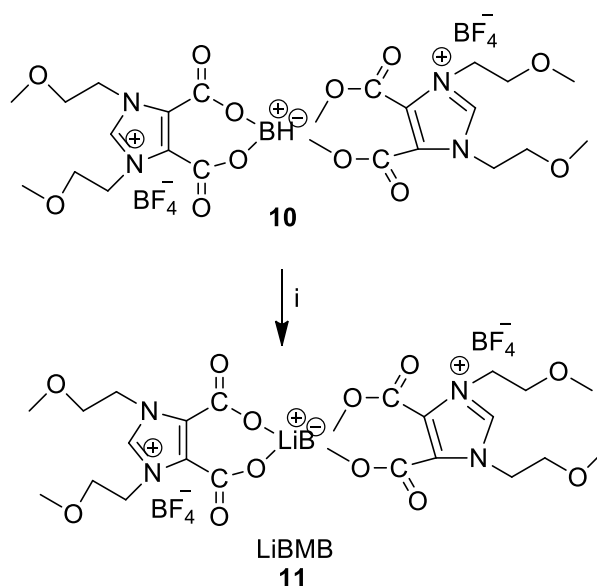
An 8-arm block liquid crystalline copolymer (8-PEG-MALC), 8-arm poly(ethylene glycol) (8-PEG), polyethylene glycol diacrylate (PEGDA), and LiTFSI composite polymer electrolyte were developed (Figure 2) [37]. The branched 8-PEG provides high ionic conductivity, PEGDA improves mechanical modulus, and the 8-arm LC copolymer tunes the electrolyte morphology. Thermal annealing produced transparent, flexible films with nanoscale phase-separated ion-conducting channels. The highest ionic conductivity achieved was $6.2 \times 10^{-5} \text{ S cm}^{-1}$ at ambient temperature. LiFePO $_4$ /Li cells with this electrolyte demonstrated excellent cycling stability at 95°C. These results suggest good compatibility with flexible all-solid-state batteries, although interfacial resistance and scalability remain areas for further assessment.



Reagents and conditions: (i) Crosslinking/self assembly

Figure 2. Composite polymer electrolyte incorporating 8-arm block liquid-crystalline copolymer polyethylene (glycol) diacrylate (PEGDA) and bistrifluoromethanesulfonimide lithium salt (LiTFSI).

Traditional lithium batteries, which combine polymer hosts, lithium salts, and volatile plasticizers with separators, face issues such as poor thermal stability, flammability, and dendrite formation. To address this, solid-state electrolytes (SSEs) based on poly(ethylene oxide) (PEO) and lithium bis(modified imidazole)borate (LiBMB) thermotropic ionic liquid crystals were developed (Figure 3) [38]. Ordered ion-conductive nano-pathways enabled high ionic conductivity ($0.45 \times 10^{-3} \text{ S cm}^{-1}$ at 30°C , measured by AC impedance in a stainless steel/Li symmetric cell), a Li-ion transference number of 0.54, and a diffusion coefficient of $2.33 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$. $\text{LiFePO}_4/\text{SSE}/\text{Li}$ cells exhibited an initial discharge capacity of $\sim 145.5 \text{ mAh g}^{-1}$ at 0.1 C. The SSEs provide improved dendrite suppression and interfacial stability compared with conventional liquid electrolytes.



Reagents and conditions: (i) LiOH, 8h, 80°C

Figure 3. Solid electrolyte associated with LiBMB/PEO.

PEO-based SPEs are promising for high-safety LIBs but often suffer from low ionic conductivity due to high crystallinity. To address this, researchers polymerized nematic liquid crystals (LCs) and ionic liquids (ILs) into free-standing electrolytes with layered nanostructures

(Figure 4) [39]. UV photopolymerization immobilized the LC, while IL insertion facilitated rapid ion transport. The resulting electrolyte achieved a high room-temperature ionic conductivity of $2.14 \times 10^{-2} \text{ S cm}^{-1}$, a wide electrochemical window of 4.8 V, and compatibility with lithium metal. $\text{LiFePO}_4/\text{Li}$ cells exhibited an average discharge capacity of 150 mAh g^{-1} . Compared with conventional ILs, ionic liquid crystals provide long-range order, enabling stable ion channels that enhance transport and reduce interfacial resistance.

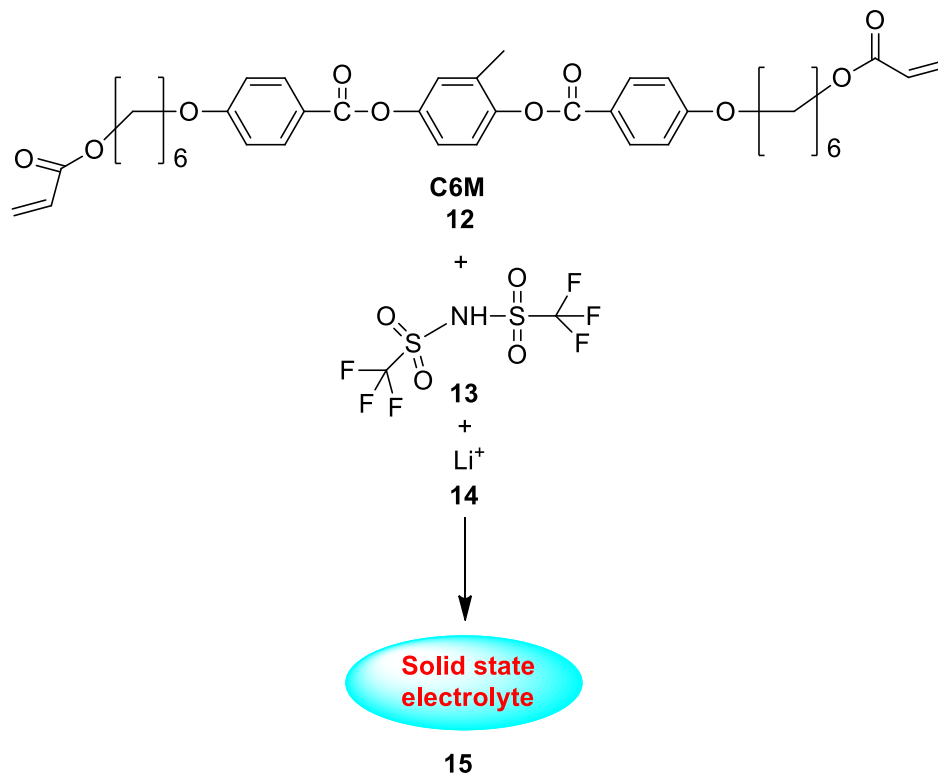
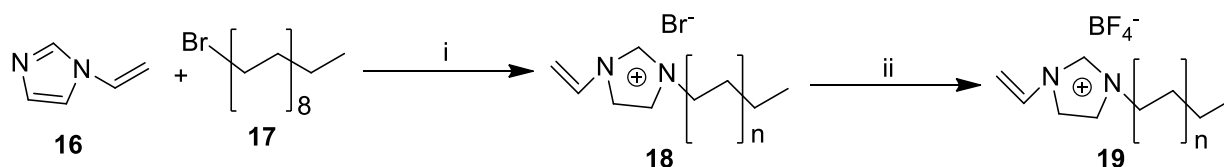


Figure 4. Solid-state electrolyte by nematic liquid crystal (C6M), lithium salt (1-ethyl-3-methylimidazolium bis (trifluoromethylsulfonyl) imide).

Free-standing ILC-based SPEs were fabricated using photopolymerization of ILC/PEGDA/PEG dimethyl ether/ LiBF_4 (Figure 5) [40]. The SPEs showed ionic conductivity of $1.96 \times 10^{-4} \text{ S cm}^{-1}$ at 30°C , a wide electrochemical window (5.2 V), and a Li^+ transference number of 0.6. $\text{LiFePO}_4/\text{Li}$ cells demonstrated stable cycling ($\sim 164 \text{ mAh g}^{-1}$ over 375 cycles at 0.2 C) and effective dendrite suppression, even at 0°C .



ILC/poly (ethylene glycol) diacrylate (PEGDA)/poly (ethylene glycol) dimethyl ether PEGDE/ LiBF_4

Reagents and conditions: (i) Acetonitrile, 60°C , 3 days, (ii) ion exchange, NaBF_4

Figure 5. Solid polymer electrolyte by ILC/poly (ethylene glycol) diacrylate (PEGDA)/poly (ethylene glycol) dimethyl ether PEGDE/ LiBF_4 .

Discotic liquid crystal-based cross-linked SPEs (DLCCSPEs) were developed via one-pot photopolymerization of oriented reactive discogens, PEGDA, and lithium salts (Figure 6) [41]. Macroscopic alignment of self-assembled columns, immobilized through UV curing, produced regulated ion-conductive channels. $\text{LiFePO}_4/\text{Li}$ cells with aligned DLCCSPEs exhibited initial discharge capacities of 164 mAh g^{-1} at 0.1°C and good rate performance at C-rates of 0.5, 1, and 0.2 C. Room-temperature performance was also improved (124 mAh g^{-1} at

0.2°C), indicating that channel orientation and mechanical robustness contribute to enhanced ion transport.

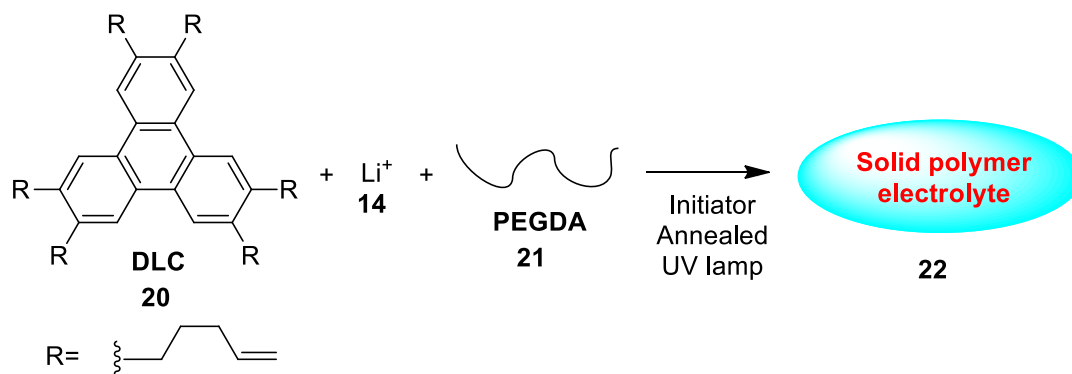


Figure 6. Solid polymer electrolyte associated with PEDGA, DLC, and Li^+ .

Controlled-structure DLC-based six-arm star polymers were synthesized using sequential ATRP of styrene and PEGMA from a triphenylene-based DLC initiator (Figure 7) [42]. The resulting SPEs demonstrated ionic conductivity of $1.46 \times 10^{-4} \text{ S cm}^{-1}$ at 30°C, a Li-ion transference number of 0.37, and an electrochemical window of 5.1 V. $\text{LiFePO}_4/\text{Li}$ cells showed reversible electrochemical behavior and excellent cycling performance, highlighting the advantage of star-shaped DLC polymers in improving chain mobility, mechanical modulus, and interfacial stability.

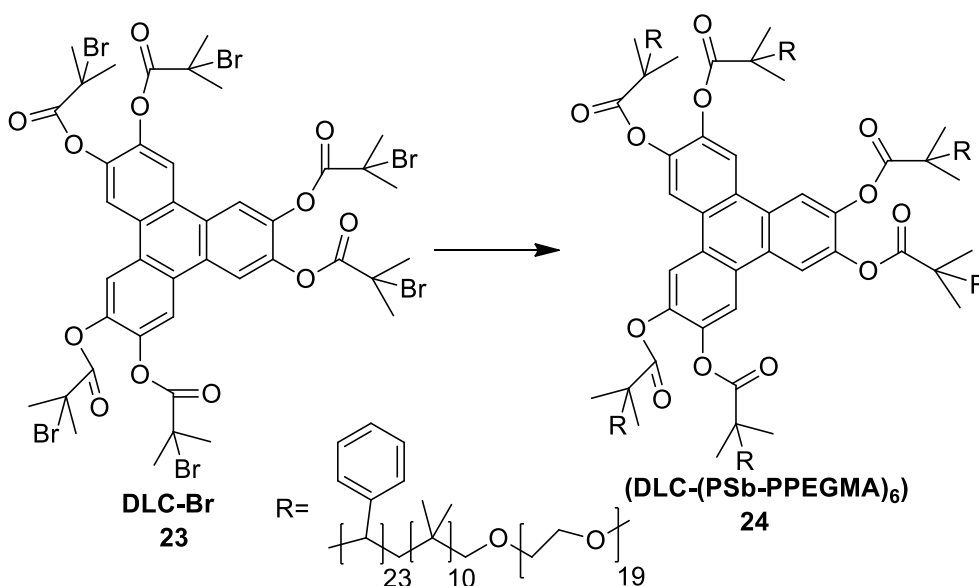


Figure 7. Solid polymer electrolyte [(DLC-(PSb-PPEGMA)₆)] along with DLC.

A hyperbranched star liquid crystalline polymer (HSLCP)-based SPE was also developed (Figure 8) [43]. The electrolyte, composed of LiTFSI and topological polymers built on biphenyl-4-carbonitrile, PCL segments, and HPG cores, exhibited high thermal stability (368°C), ionic conductivity of $5.98 \times 10^{-5} \text{ S cm}^{-1}$, wide electrochemical window (5.12 V), and Li-ion transference number of 0.63. Half-cells powered LEDs at room temperature, demonstrating adequate mechanical modulus and interfacial contact.

Bio-based ionic liquid crystal-derived SPE membranes (BILC-SPEs) were prepared using a polymeric backbone, Li salt, and cardanol-derived ILCs (Figure 9) [44]. The membranes exhibited high conductivity, porosity, wettability, and Li-ion transport number, facilitating facile ion transport. $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2/\text{Li}$ coin cells achieved a specific capacity of 160 mAh g^{-1} at 0.05°C, while LiFePO_4 cells demonstrated good rate capability and cycle

stability ($\sim 170 \text{ mAh g}^{-1}$). While the authors highlight environmentally friendly synthesis from industrial by-products, they significantly improve performance.

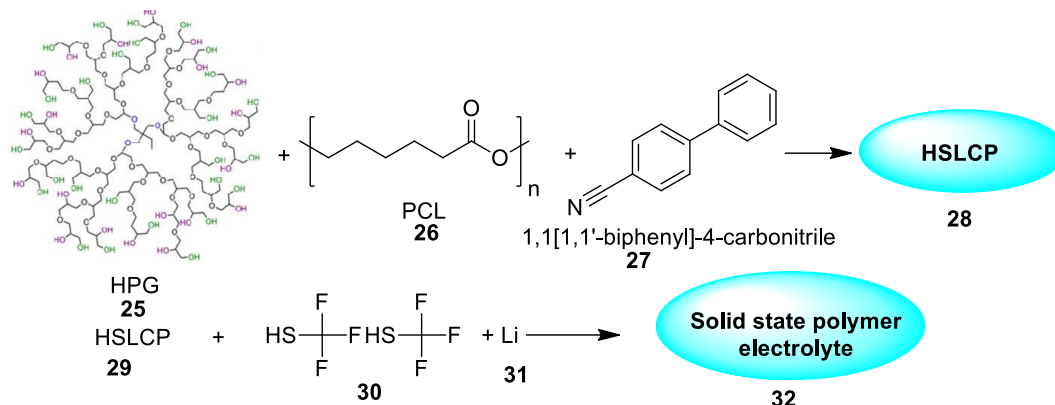


Figure 8. Solid-state polymer electrolyte comprising PCL chain segments, a topological polymer with biphenyl-4-Carbonitrile-based liquid crystal, the core of HPG, and LiTFSI.

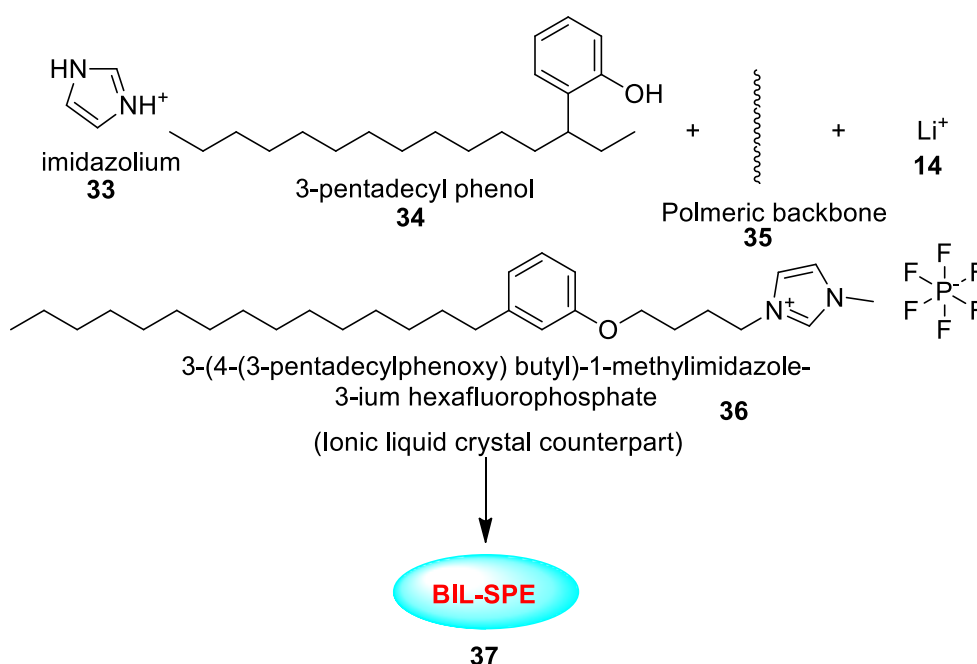


Figure 9. Biobased ionic liquid crystalline solid polymer electrolyte (BIL-SPE) synthesized from imidazolium-based 3-pentadecyl phenol (cardanol) derivative.

Finally, PEO/3PMALC-PPEGMA/10-BPCN composite electrolytes (Figure 10) [45] were developed. Star-shaped liquid-crystalline copolymers reduce PEO crystallinity, enhance chain mobility, and form ordered morphologies. The ternary blend (70/25/5) achieved an ionic conductivity of $1.85 \times 10^{-4} \text{ S cm}^{-1}$ at 80°C and $1.3 \times 10^{-5} \text{ S cm}^{-1}$ at room temperature (after thermal annealing).

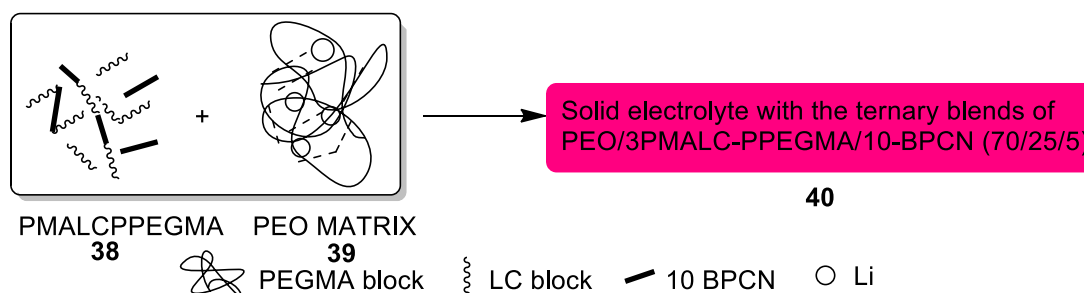


Figure 10. PEO-based solid-state composite polymer electrolytes.

These materials provide well-defined ion channels, high Li-ion transference numbers, and wide electrochemical windows, making them suitable for ambient-temperature operation in all-solid-state lithium-ion batteries.

Table 1. Highlights the key findings from the text about the solid polymer electrolytes (SPEs) and related materials for lithium-ion batteries.

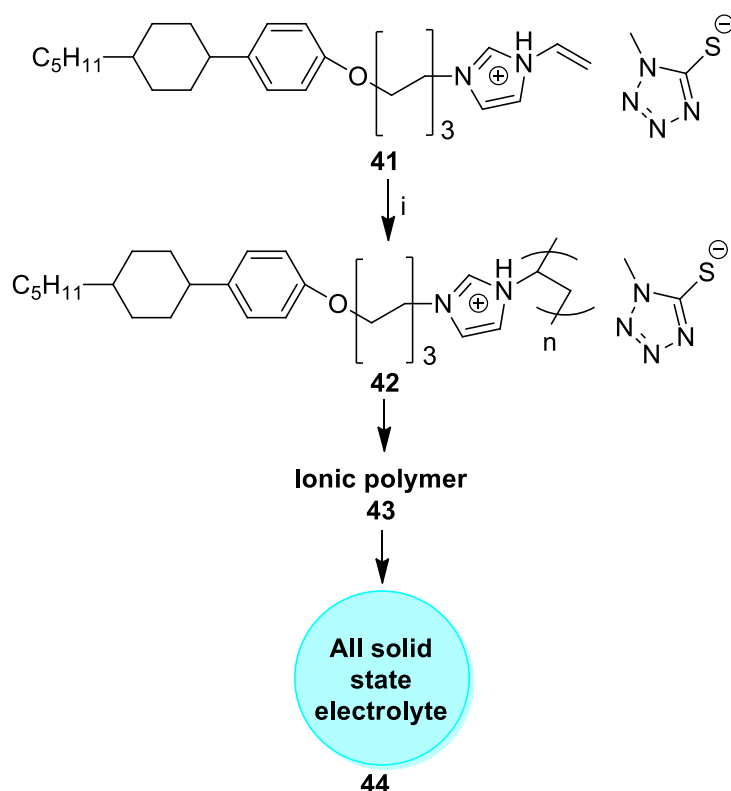
Year and author	Figure	Material	Key features	performance metrics
2020 & Chen X <i>et al.</i>	Figure 1	2D Solid Composite Polymer Electrolyte ([C16mim]BF ₄ and PMOBIm)	Enhanced thermal stability, non-flammability, and high ionic conductivity.	Ionic conductivity: 7.14×10^{-5} S cm ⁻¹ (25°C), 2.17×10^{-3} S cm ⁻¹ (95°C) - Coin cell specific capacity: 136.7 mAh g ⁻¹ (1st cycle), 118.9 mAh g ⁻¹ (40th cycle) at 0.1°C.
2020 & Cao X <i>et al.</i>	Figure 2	Composite Polymer Electrolyte (8-PEG-MALC, PEGDA, and LiTFSI)	Transparent, flexible film with high thermal stability and nanoscale ion-conductive channels.	Ionic conductivity: 6.2×10^{-5} S cm ⁻¹ (ambient temperature) - Thermal stability: 150°C - Coin cell (LiFePO ₄ /Li): Excellent charge/discharge cycle performance at 95°C.
2019 & Yuan F <i>et al.</i>	Figure 3	Flexible PEO/LiBMB SSE	Ordered ion-conductive nano-pathways and separator-free safe design.	Ionic conductivity: 0.45×10^{-3} S cm ⁻¹ (30°C) - Li ⁺ transference number: 0.54 - Initial discharge capacity: 145.5 mAh g ⁻¹ at 0.1°C (LiFePO ₄ /SSEs/Li).
2019 & Wang S <i>et al.</i>	Figure 4	Nematic Liquid Crystal-based SPE	High ionic conductivity and lithium metal compatibility due to stable ordered channels.	Ionic conductivity: 2.14×10^{-2} S cm ⁻¹ (room temperature) - Electrochemical window: 4.8 V - Coin cell discharge capacity: 150 mAh g ⁻¹ (LiFePO ₄ /Li).
2018 & Wang S <i>et al.</i>	Figure 5	ILC-based SPE (ILC/PEGDA/PEGDE/LiBF ₄)	Strong ionic conductivity and high Li ⁺ transference number with reduced dendrite formation.	Ionic conductivity: 1.96×10^{-4} S cm ⁻¹ (30°C) - Electrochemical window: 5.2 V - Cycling stability: 164 mAh g ⁻¹ at 0.2°C over 375 cycles.
2018 & Wang S <i>et al.</i>	Figure 6	DLCCSPE (Discotic Liquid Crystal-based Cross-linked SPE with PEGDA)	Oriented ion-conducting channels with excellent cycling performance and a simple fabrication process.	Ionic conductivity: High due to aligned DLC columns - Coin cell discharge capacity: 164 mAh g ⁻¹ at 0.1°C (initial), 135–149 mAh g ⁻¹ (different C-rates).
2018 & Wang S <i>et al.</i>	Figure 7	DLC-based Star Copolymer SPE (DLC-(PSb-PPEGMA) ₆)	Long-range molecular orientation with high ionic conductivity and lithium-ion compatibility.	Ionic conductivity: 1.46×10^{-4} S cm ⁻¹ (30°C) - Electrochemical window: 5.1 V - Improved cycling performance and reversible reactions.
2018 & Wang S <i>et al.</i>	Figure 8	Bio-based Ionic Liquid Crystal (BILC-SPE)	Derived from low-cost industrial waste, offering environmentally friendly and efficient energy storage solutions.	Specific capacity: 160 mAh g ⁻¹ (LiNi _{1/3} Co _{1/3} Mn _{1/3} O ₂ at 0.05°C) - Near theoretical capacity: ~170 mAh g ⁻¹ (LiFePO ₄ cathode).
2017 & Sasi R <i>et al.</i>	Figure 9	HSLCP-based SPE (Biphenyl-4-Carbonitrile, PCL, HPG Core with LiTFSI)	High thermal stability and ionic conductivity with excellent cycling and rate capabilities.	Ionic conductivity: 5.98×10^{-5} S cm ⁻¹ - Electrochemical window: 5.12 V - Can power white LED bulbs even at room temperature.
2014 & Tong Y <i>et al.</i>	Figure 10	PEO-based Composite Polymer Electrolyte (PEO/3PMALC-PPEGMA/10-BPCN)	Organized morphology and lamellar phase structure for efficient lithium transfer.	Ionic conductivity: 1.85×10^{-4} S cm ⁻¹ (80°C), 1.3×10^{-5} S cm ⁻¹ (room temperature) - Enhanced miscibility and reduced PEO crystallinity.

This table encapsulates the essential details about each SPE material, showcasing their composition, unique features, and performance metrics for lithium-ion battery applications.

9.2. Dye-sensitized solar cells.

Solar energy harvesting with a high yield is still a key issue in the context of sustainable development, despite the resource's clean, inexhaustible, and easy availability. In the LC prospect, solid electrolytes enhanced the performance of dye-sensitized solar cells when applied (Table 2).

Researchers fabricated an all-solid-state polymer electrolyte based on a thiolate/disulfide redox couple through in situ polymerization of a lamellar liquid-crystalline precursor (Figure 11) for DSSC applications [46]. The polymerization process preserved the pre-organized lamellar nanoarchitecture while simultaneously enhancing interfacial contact between the electrolyte and the mesoporous TiO₂ photoanode. Electrochemical analysis indicated that the polymerized electrolyte retained ionic transport characteristics comparable to those of the liquid-crystalline precursor, suggesting that continuous ion-conduction channels were maintained after solidification. The resulting solid-state DSSCs operated thermally stably, with power conversion efficiencies (PCEs) exceeding 2% over 35–90°C. Although these efficiencies remain lower than those of state-of-the-art liquid-electrolyte DSSCs (>11–14% under AM 1.5G illumination), the improved thermal durability and structural stability highlight the potential of in situ nanostructured polymer electrolytes for scalable solid-state devices.



Reagents and conditions: (i) In situ thermal polymerization

Figure 11. Solid-state crystal electrolyte with thiolate or disulfide.

For the development of reliable quasi-solid-state DSSCs, nanostructured liquid-crystalline (LC) electrolytes have been designed in two principal configurations (Figure 12): (i) noncovalent assemblies composed of I₂-doped imidazolium ionic liquids combined with carbonate-terminated mesogenic molecules, and (ii) covalently bonded single-component mesogens incorporating imidazolium moieties [47]. In both systems, flexible oligo-oxyethylene spacers connect the mesogenic and ionic segments, suppressing crystallization and enhancing segmental mobility relative to alkyl-linked analogs. The diffusion coefficient of I₃[−] in

noncovalent assemblies was reported to be more than ten times higher than in covalent systems, reflecting reduced ion-pairing interactions and more continuous ionic pathways. Consequently, noncovalent LC-based DSSCs achieved PCE values up to $5.8 \pm 0.2\%$ at 30°C , while covalent systems exhibited superior high-temperature performance, reaching $2.4 \pm 0.1\%$ at 120°C and outperforming noncovalent counterparts above 90°C . These differences can be attributed to the balance between ionic mobility and structural rigidity, which influences charge-transfer resistance (R_{ct}) and recombination kinetics at the $\text{TiO}_2/\text{electrolyte}$ interface. Although operational stability beyond 1000 hours was reported, meaningful benchmarking requires specifying illumination intensity, encapsulation conditions, and the ambient environment.

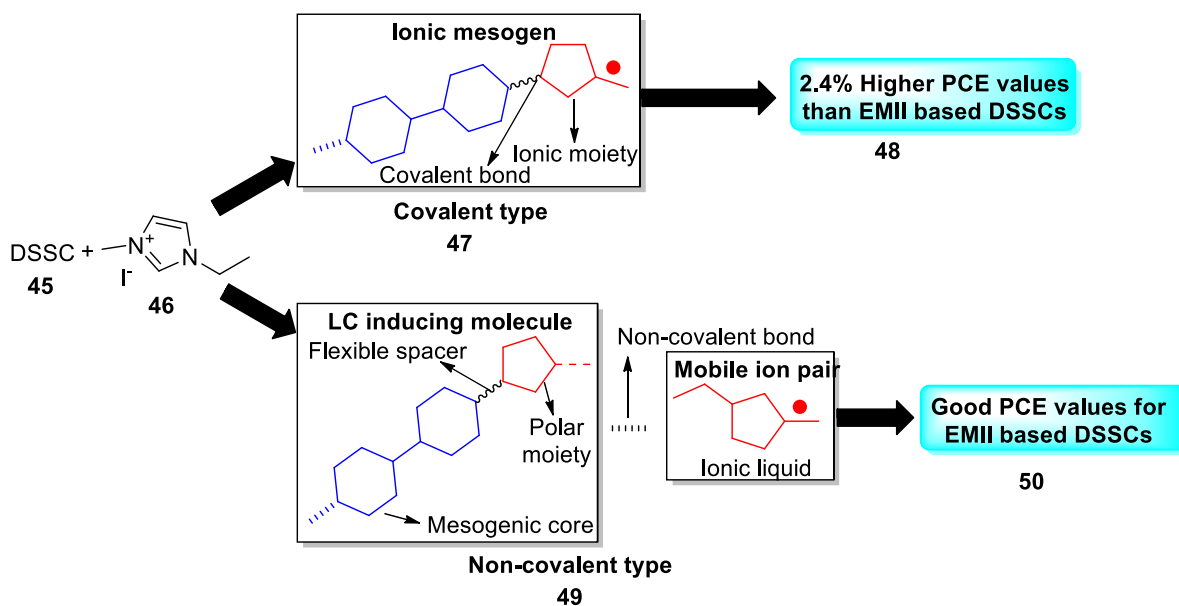


Figure 12. DSSC containing 1/ 1-ethyl-3-methylimidazolium iodide (EMII) for good PCE values in SPE.

The role of LC phase behavior in governing interfacial charge-transfer processes was further examined using double-alkyl functionalized imidazolium triiodide ionic liquid crystals (Figure 13) [48]. It was observed that optimal photovoltaic performance occurred in the smectic-C phase, where ordered ionic domains enable directional hole transport while suppressing back-electron transfer from TiO_2 to I_3^- species. The efficiencies reported (1.5–3.9%, depending on illumination intensity) remain modest compared with optimized liquid systems; however, the findings underscore the importance of phase-dependent ionic organization in minimizing recombination and maintaining dye regeneration efficiency.

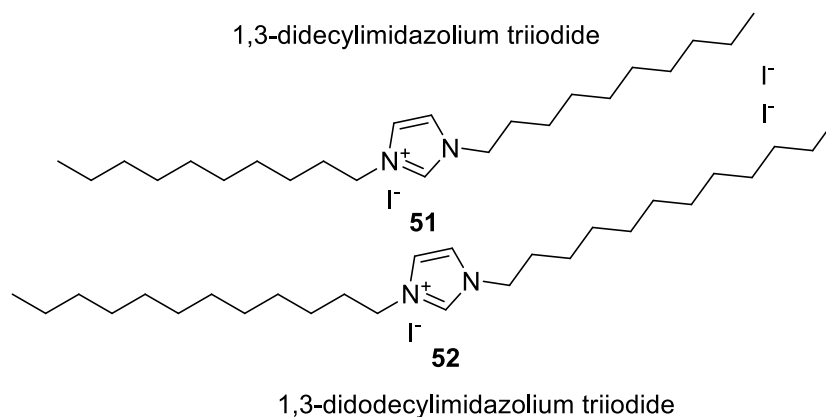


Figure 13. A pair of 1,3-didecylimidazolium triiodide.

The absence of alternative redox couples in LC systems further motivates the exploration of iodine-free electrolytes to mitigate corrosion, sublimation, and parasitic visible-light absorption.

Iodine-free solid-state DSSCs employing vinyl-functionalized imidazolium electrolytes (EBII and EVII, Figure 14) were developed to address these limitations [49]. Structural analysis confirmed highly ordered lamellar arrangements, with EBII exhibiting a larger interlayer spacing (10.44 Å) than EVII (4.01 Å), facilitating enhanced ionic diffusion. Differential scanning calorimetry revealed stronger intermolecular interactions in EVII, correlating with higher melting temperatures but reduced ionic mobility. Electrochemical impedance spectroscopy demonstrated lower charge-transfer resistance and reduced recombination in EBII-based devices, resulting in a higher PCE of 4.7% (100 mW cm⁻²) compared to 3.8% for EVII. These findings establish a direct link between lamellar spacing, ion transport, and recombination suppression.

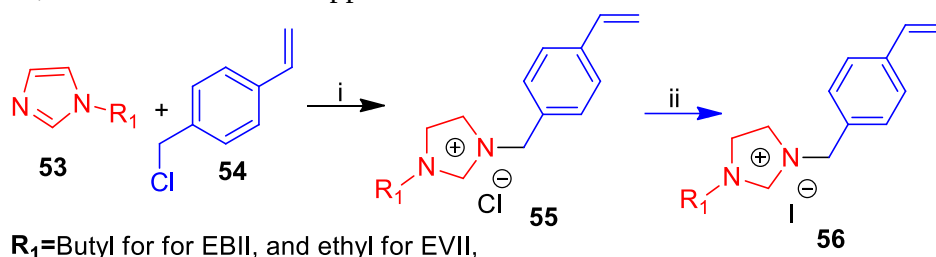


Figure 14. SPE from ILC using a single aliphatic C=C bond in EBII and an added aliphatic C=C bond in EVII.

Composite solid-state electrolytes incorporating carbon materials with binary ionic systems (EMII/EMIBF₄) have also been investigated [50]. Carbon components function both as physical gelation matrices and electrocatalytic sites for I₃⁻ reduction at the counter electrode. Photovoltage transient and impedance analyses indicated that adding carbon nanotubes reduces interfacial recombination and enhances charge transport within the electrolyte. Replacement of carbon black with multi-walled or single-walled carbon nanotubes improved efficiencies to 3.53% and 4.01%, respectively. Devices employing SWCNT–binary CTI electrolytes exhibited long-term stability exceeding 1000 hours at room temperature; however, standardized light-soaking conditions were not explicitly detailed. Compared with solvent-based electrolytes, these systems showed lower interfacial resistance and greater structural robustness.

The incorporation of the nematic liquid crystal 4-cyano-4'-n-heptyloxybiphenyl into PVDF-based polymer gel electrolytes (Figure 15) has been shown to enhance light harvesting in DSSCs [51].

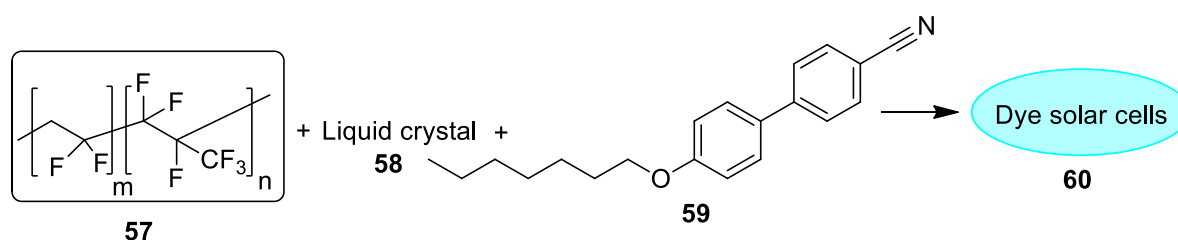


Figure 15. SPE in DSC with 4-cyano-4'-n-heptyloxybiphenyl and PVDF.

Although the presence of LC domains slightly reduces ionic conductivity due to constrained I⁻/I₃⁻ diffusion, the formation of a light-scattering network increases the optical path length within the device. This light-trapping mechanism improves photon absorption by

the sensitizer, leading to enhanced short-circuit current density (J_{sc}). The resulting increase in photocurrent compensates for moderate fill-factor reductions associated with slower ionic diffusion. Devices retained more than 92% of their initial PCE after 1000 hours under storage conditions, though a comprehensive stability evaluation under continuous illumination is required for direct comparison with established DSSC standards.

Further refinement of LC-based quasi-solid-state electrolytes enabled efficiencies up to 8.18% under AM 1.5 illumination during initial testing [52]. The enhanced performance was attributed to the electrolyte layer's increased optical thickness, which promoted multiple scattering events and extended photon residence time. This improvement in incident photon-to-current efficiency (IPCE) demonstrates the effectiveness of LC-induced light management strategies. Nonetheless, systematic analysis of recombination kinetics and long-term photothermal durability remains necessary.

We also developed a series of polymeric electrolytes incorporating liquid crystals such as E7 and ML-0249 within a polyacrylonitrile (PAN) matrix to regulate ionic ordering and enhance redox-species transport (Figure 16) [53]. These quasi-solid-state systems exhibited improved ionic conductivity and favorable interfacial contact with dye-coated TiO_2 . The optimized ML-0249: PAN (1:1) composition achieved a PCE of 6.29%, comparable to certain liquid-electrolyte DSSCs. Polarized optical measurements confirmed that LC alignment facilitates anisotropic ion migration, reducing transport resistance and promoting efficient dye regeneration. Enhanced electron diffusion lengths and suppressed recombination contributed to improved photovoltaic response.

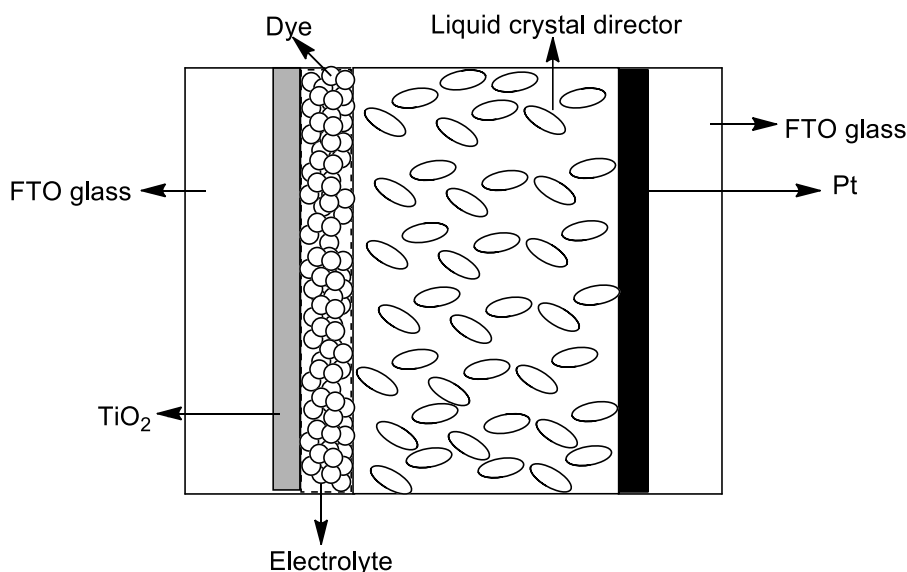


Figure 16. SPE in DSSC showing reduced interaction with the dye-covered TiO_2 surface.

Table 2. Highlights the key findings from the text about the solid polymer electrolytes (SPEs) and related materials for DSSC.

Year and author	Figure	Material	Key features	Performance metrics
2020 & Li X <i>et al.</i>	Figure 11	Thiolate/Disulfide-based solid-state electrolyte	In-situ polymerization maintains lamellar nanostructure, thermally stable from 35–90°C.	PCE > 2%.
2016 & Hgberg D & <i>et al.</i>	Figure 12	1/1-Ethyl-3-methylimidazolium iodide (EMII)	Noncovalent ionic LC assembly enhancing ion transport and PCE; flexibility of oligooxyethylene spacer suppressing crystallization.	PCE = 5.8% at 30°C; long-term stability >1000 hours.
2013 & Costa R D <i>et al.</i>	Figure 13	1,3-Didecylimidazolium triiodide	Stable dye rejuvenation and hole transmission in smectic-C phase;	PCE = 1.5% (1 sun), 3.9% (0.25 sun); limited optimization.

Year and author	Figure	Material	Key features	Performance metrics
			single-component ionic liquids for improved performance.	
2013 & Chi W S <i>et al.</i>	Figure 14	EBII and EVII	I2-free electrolytes; lamellar structures with distinct d-spacing values for better ion transport and reduced recombination.	PCE = 4.7% (EBII) and 3.8% (EVII) at 100 mW/cm ² .
2011 & Wang M <i>et al.</i>	Figure 15	4-Cyano-4'-n-heptyloxybiphenyl	Enhanced light trapping and improved photoelectric conversion efficiency through liquid crystal in PVDF-based polymeric gel electrolyte.	Retains >92% PCE after 1000 hours; initial PCE = 8.18%.
2009 & Kim S C <i>et al.</i>	Figure 16	ML-0249 + Polyacrylonitrile (PAN) LC electrolyte	Quasi-solid-state DSSC electrolyte with liquid-like ionic conductivity and effective redox transmission over aligned liquid crystal.	PCE = 6.29% at a 1:1 weight ratio of ML-0249:PAN.

This table encapsulates the essential details about each SPE material, showcasing their composition, unique features, and performance metrics for DSSC applications.

9.3. Sodium-ion battery.

The sodium-ion battery (NIB) is a rechargeable battery that functions similarly to a lithium-ion battery but uses sodium ions (Na⁺) as charge carriers. Its operating principle and cell structure are nearly comparable to commercially available lithium-ion batteries, except that it uses sodium compounds instead of lithium compounds (Table 3). The enormous natural abundance of sodium is the most significant benefit of sodium-ion batteries. This might lower the cost of manufacturing sodium-ion batteries in comparison to lithium-ion batteries.

The solution casting approach was used to create new PEO/E8 liquid crystal-based composite solid polymer electrolyte membranes complexed with NaIO₄ salt (Figure 17). X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, micro-Raman, and X-ray photoelectron spectroscopy (XPS) were used to investigate the composite-salt complexation. The addition of NaIO₄ to the electrolyte membrane matrix resulted in a reduction in the proportion of the crystalline part in the matrix, according to DSC tests. The EIS investigations showed that increasing the concentration of NaIO₄ increased the ionic conductivity of the electrolytes, and in the current investigation, the PEO/E8 electrolyte complexed with 10% NaIO₄ had a higher room temperature ionic conductivity of 1.05 X 10⁻⁷ S/cm [54].

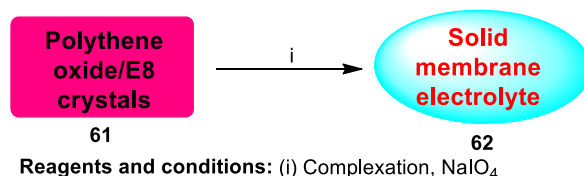


Figure 17. Solid membrane electrolyte with NaIO₄, polyethylene oxide/E8 liquid crystal.

Table 3. Highlights the key findings from the text about the solid polymer electrolytes (SPEs) and related materials for sodium-ion batteries.

Year and author	Figure	Material	Key features	Performance metrics
2019 & Koduru H K <i>et al.</i>	Figure 17	PEO/E8 composite solid polymer electrolyte	Composite electrolyte matrix complexed with NaIO ₄ ; reduced crystallinity; improved ionic conductivity with NaIO ₄ addition.	Ionic conductivity = 1.05 × 10 ⁻⁷ S/cm at room temperature.

This table summarizes the essential details of each SPE material, including their composition, unique features, and performance metrics for sodium-ion battery applications.

9.4. Energy storage devices.

Because most inorganic solid electrolytes offer good mechanical strength, high thermal stability, and non-flammability, and flexible polymer solid electrolytes can inhibit lithium dendrite formation, composite solid electrolytes (Table 4) are effective for reducing the safety hazards of energy storage devices.

Closo-carborane anions (Figure 18), particularly $[\text{HCB}_{11}\text{H}_{11}]^-$ and $[\text{HCB}_9\text{H}_9]^-$, and their derivatives have historically been employed as counteranions for straightforward Lewis acid catalysis, platforms for stoichiometric and catalytic functionalization, weakly coordinating anions to isolate reactive intermediates, and constituents of materials like liquid crystals. It focuses on these anions' nonclassical uses in the modern world. The clusters serve as covalently bound spectator substituents for coordination chemistry and improved catalyst design, as well as dianionic C σ -binding ligands. They show promise as solution-based and solid-state electrolytes in Li, Na, and Mg batteries [55].

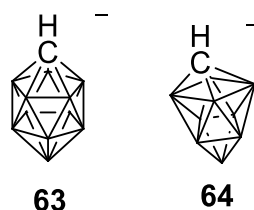


Figure 18. Closo-carborane anions.

9.5. Electrolytic membrane.

LCs are of great interest for modern electrochemical devices, particularly energy devices such as lithium batteries, fuel cells, and solar cells, whose development is projected to address current challenges in renewable energy and global warming.

Cross-linkable gemini ionic liquid crystals are created by jacketing the diammonium moiety between two biphenyl benzoate mesogens (Figure 19). Anisotropic films are created by photopolymerizing macroscopically aligned gemini ionic liquid crystals for ion conduction. The monolayer nanostructure is formed in the films, according to small-angle X-ray scattering (SAXS) measurements, and the smectic layers are perpendicular to the film surface, according to scanning electron microscopy (SEM) observations. The films have considerable anisotropy in ion conduction, according to electrochemical impedance spectroscopy (EIS) analysis. Ion conduction across the film is improved, although it is hampered inside the film's plane. At 180°C, the film's ionic conductivity in the vertical direction approaches $10^{-3} \text{ cm S}^{-1}$, and the observed anisotropy (the ratio of observed conductivities in the vertical direction to in parallel to the film) is 100–350. Photopolymerization of cross-linkable gemini ammonium liquid crystals shows great promise for developing solid electrolytes for electrochemical devices [56].

Polyethylene glycol is a petroleum-derived polyether chemical with several uses ranging from industrial manufacture to medicine. Depending on its molecular weight, PEG is also known as polyethylene oxide (PEO) or polyoxyethylene (POE). PEG's structure is typically described as $\text{H}-(\text{O}-\text{CH}_2-\text{CH}_2)_n-\text{OH}$. Polylactic acid, also known as polylactide, is a thermoplastic polyester with the backbone formula n or $[-\text{CHCO}-]_n$ that is made by condensing

lactic acid $-\text{CHCOOH}$ with the removal of water. Lactide $[-\text{CHCO}-]_2$, the cyclic dimer of the basic repeating unit, may also be produced through ring-opening polymerization.

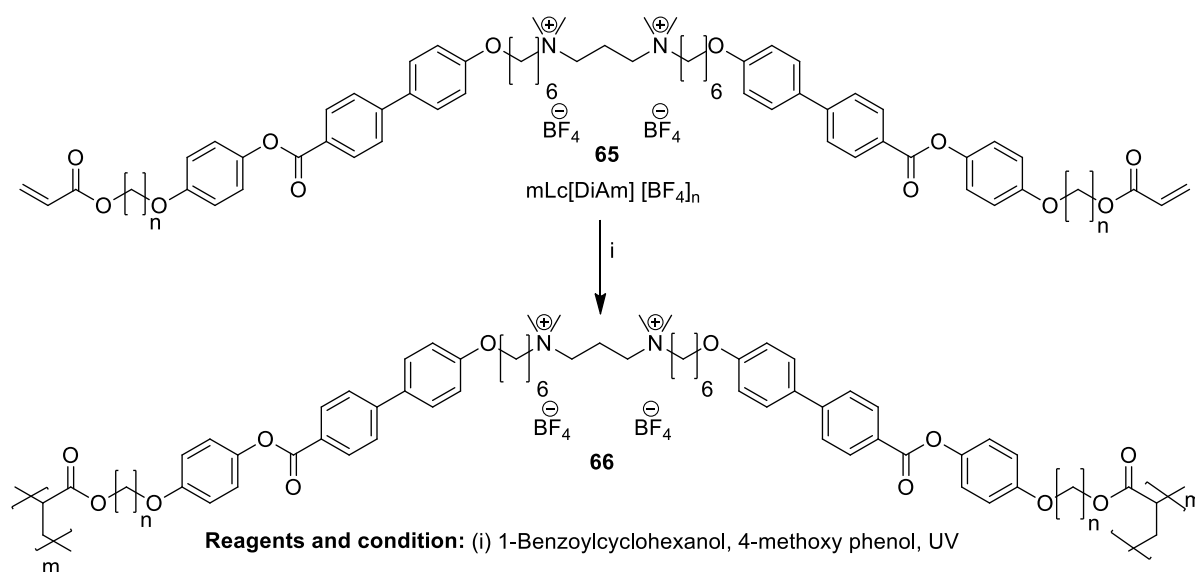


Figure 19. Gemini ammonium tetrafluoroborate nanostructured films in a single layer, as the diammonium molecules are clustered into lamellae all over the layer.

A variety of solid polymer electrolytes (SPEs) based on poly (ethylene oxide)/polylactic acid (PEO/PLA) with liquid crystal ionomer (LCI) intercalated montmorillonite (MMT) nanocomposites (LCI-MMT) were produced using the solution mixing technique (Figure 20). The effects of LCI-MMT on the thermal, ionic conductivity, crystallization, and structural properties of solid polymer electrolytes have been investigated. It was shown that adding LCI-MMT to the mix reduced the crystallinity of PEO while increasing the crystallinity of PLA. At room temperature, the maximal ionic conductivity for 0.5 wt% LCI-MMT is found to be in the range of $1.05 \times 10^{-5} \text{ Scm}^{-1}$, which is greater than that of the LCI-MMT-free polymer electrolyte ($5.36 \times 10^{-6} \text{ Scm}^{-1}$) [57].

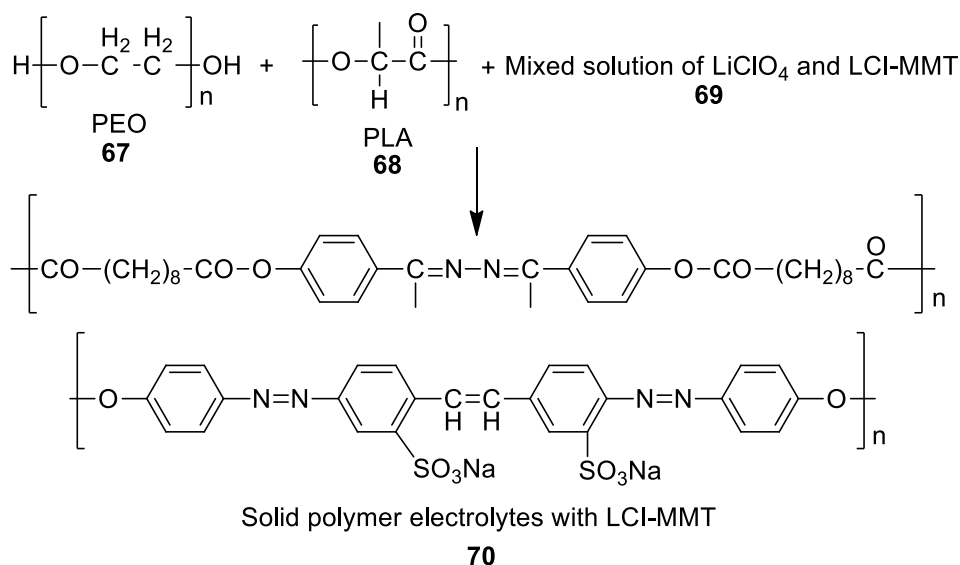


Figure 20. Solid polymer electrolyte with LCI-MMT.

Due to its rigid conformation, ease of synthesis, and structural controllability, mesogen-jacketed liquid crystalline polymer (MJLCP) has received a lot of interest. The self-assembly of MJLCP-based block copolymers (BCPs) is briefly discussed in this feature article, with a

The AIE characteristics of bulk tetraphenylethene (TPE) derivatives with nonpolar and polar outer chains are investigated. At room temperature, nonpolar dodecyl and polar di(ethylene oxide) chains in bulk TPE derivatives are in liquid crystal (LC) and crystalline phases, respectively (Figure 22). Because the mobile LC character of TPE derivatives in bulk is effective in minimizing the number of undesirable non-emissive local sites in aggregates and inducing a homogeneous zigzag-stacked columnar structure with j-type coupled transition dipoles of the TPE derivatives, it is critical for high AIE efficiency. AIE luminogens' mobile LC properties can be advantageous for highly efficient solid-state emission. Apart from the crystalline phase after drying, TPE (tetraphenylethene) derivatives were investigated for their emissive capabilities with mobile liquid crystals. When TPE compounds are coupled with nonpolar external dodecyl chains, columnar LC phases form at room temperature. These encourage J-type aggregation instead of H-type aggregation. As a result, aromatic interactions will occur. The number of external dodecyl chains in bulk determines aromaticity and mobility in the LC phase. The effect of shifting thermally activated TPE molecules from 140°C to the isotropization temperature was also investigated. At a given temperature, the restrictions are incorrect stacking and stiffness in structural packing. The findings lay the groundwork for further research into liquid crystal aggregation-induced emission (AIE) chemicals and their emissive capabilities in both solid and condensed phases. Based on their emission qualities, AIE may also be used in OLEDs [60].

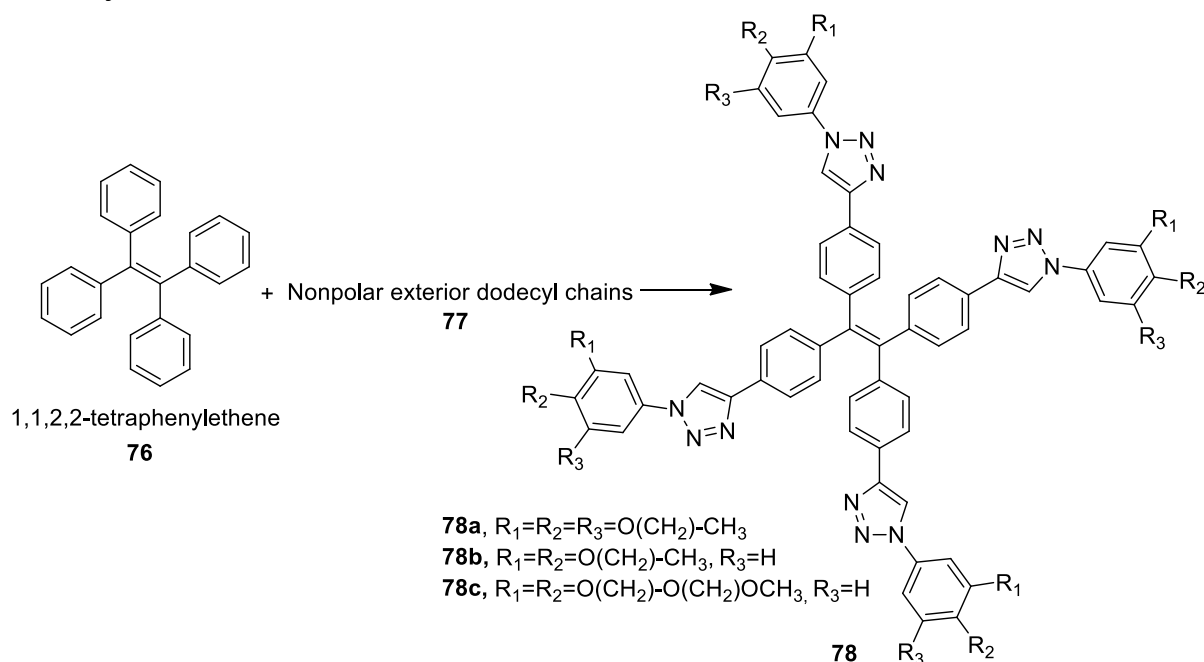


Figure 22. TPE derivatives conjugated with nonpolar exterior dodecyl chains promote J-type aggregation.

The solution casting method was used to create a new PEO-based combination of solid polymer electrolytes, doping liquid crystalline ionomers (LCI), PEO/PMMA/LiClO₄/LCI, and PEO/LiClO₄/LCI. LCI evenly diffused into the solid electrolytes and restrained phase separation of PEO and PMMA, according to scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) studies (Figure 23). LCI reduces the crystallinity of blended solid polymer electrolytes, according to data from differential scanning calorimetry (DSC). Thermogravimetric analysis (TGA) revealed that LCI increased the thermal stability of PEO/PMMA/LiClO₄ blends while also preventing phase separation of PEO/PMMA. The results of infrared spectra showed that there is contact between Li⁺ and O, as well as LCI, which encourages the synergistic actions of PMMA and PEO. In PEO/PMMA blends, the

concentration of LiClO₄ enhances the electrolyte's conductivity, according to the EIS results, although it increases slowly initially, peaking at 2.53×10^{-4} S/cm at 1.0 % LCI. The addition of 1.0% LCI increases the electrolyte's conductivity because LCI encourages compatibility and interaction between PEO and PMMA. The rigidity produced by the crystal unit, soft segment, and terminal ionic groups in LCI all work together to increase PEO/PMMA interfacial contact, and the reduction of PEO's degree of crystallinity facilitates Li⁺ migration more easily [61].

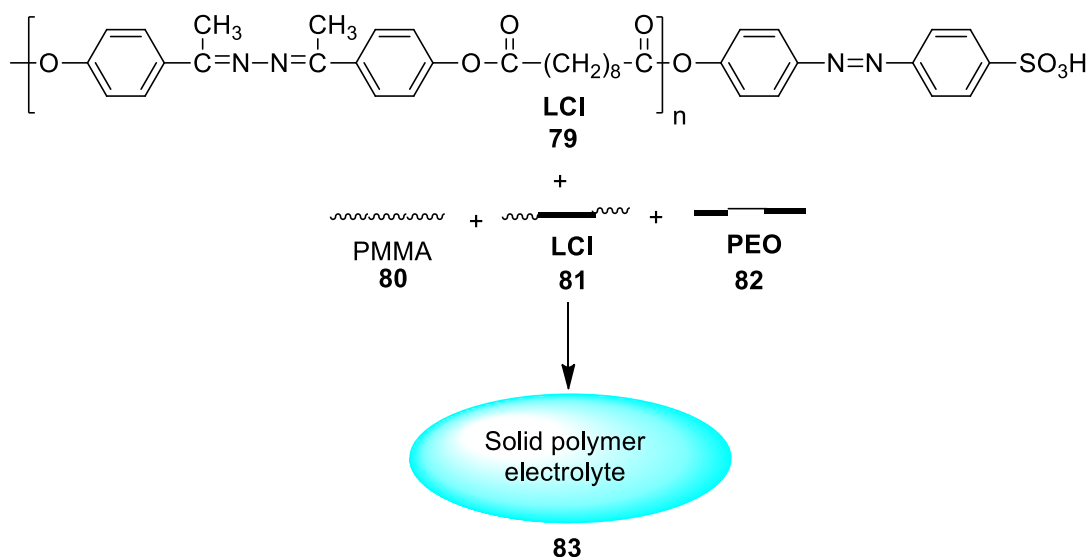


Figure 23. Solid polymer electrolyte doped with liquid crystalline ionomers (LCI), PEO/ PMMa/ LiClO₄/LCI, and PEO/ LiClO₄/LCI, the new blends based on PEO.

The azobenzene twin molecule (P4P) with the structure phenylazobenzenetetraethyleneglycol-phenylazobenzene as the AA monomer and diols like diethylene glycol, tetraethylene glycol (TEG), and hexaethylene glycol as the BB comonomer was used to make three main-chain thermotropic liquid crystalline (LC) azobenzene polymers. P4P's terminal -(O)OMe units aided transesterification with diols and the formation of polyesters. Smectic mesophases were stable in all polymers.

Poly(P4PTEG) was chosen as one of the polymers for producing composite polymer electrolytes with LiCF₃SO₃, and ionic conductivity was evaluated using ac impedance spectroscopy. It is further polymerized with diols like HEG, DEG, and TEG to generate LC azobenzene polyesters (Figure 24). They act as an excellent supporter for ionic conduction and are thermally stable following the complexation of this photoresponsive material with a lithium salt. The monomer and twin azobenzene are the building components in this case. It demonstrates ionic conductivity in a 10^{-5} Scm⁻¹ stretch for a polymer/0.3 Li complex at room temperature of around 25°C, and when the temperature is raised above 65°C, the ionic conductivity may grow to 10^{-24} Scm⁻¹. Compared to the ordered LC phase, the glass transition has a more significant influence on ionic conductivity. Compared to segments organized as LC in these polymers, the mobility of the segments can be improved by the ethylene glycol units. The reversibility in ionic conductivity is seen after irradiation of the polymer/0.3 Li salt combination. The conductivity rises when exposed to UV light, but it decreases when exposed to visible light [62].

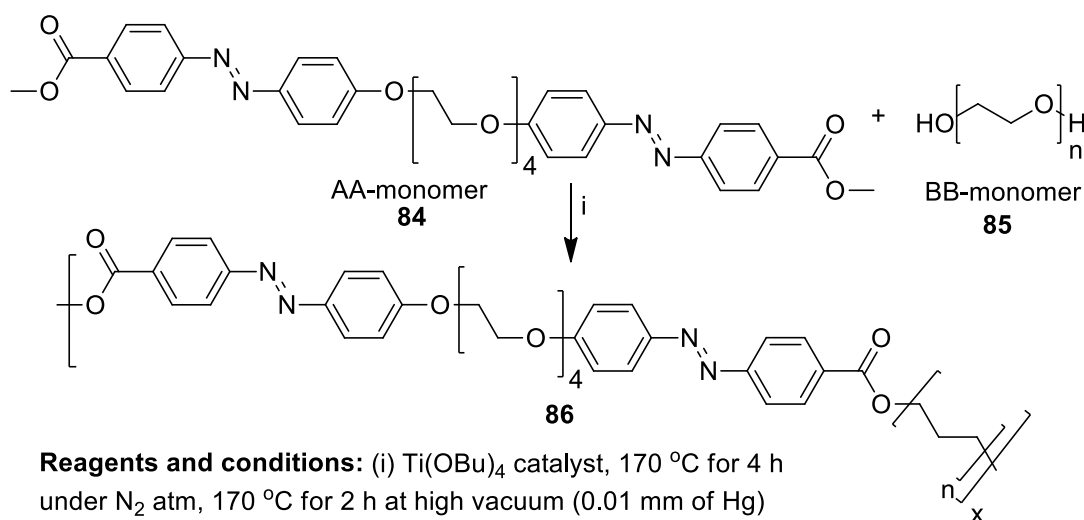


Figure 24. Oligo (ethylene oxide) chains incorporated in azobenzene- AA type monomers resulting in SPE.

A revolutionary low-cost method for creating large-format flexible RGB phosphor sheets for use in lighting and displays is provided (Figure 25). Any traditional down-conversion/up-conversion phosphor or non-phosphor optical powder materials, independent of particle size, shape, or composition, can be used in the process. Roll-to-roll production of monochromatic and patterned phosphor sheets in widths of more than 50 inches and lengths greater than 50 meters is possible. With monolayer control over phosphor coating thickness and greater than 5% color consistency, substrate thickness may range from 50 microns (2 mils) to over 500 microns (20 mils). High-performance remote phosphor sheets for phosphor-converted white LEDs with ultra-high color rendering index ($\text{CRI} > 96$) and correlated color temperature (CCT) ranging from 2700 K to over 8000 K are now being produced with this technique. When paired with a blue LED, a tailored red/green phosphor film has been proven to offer 100 % of the NTSC color spectrum for LCD display applications [63].

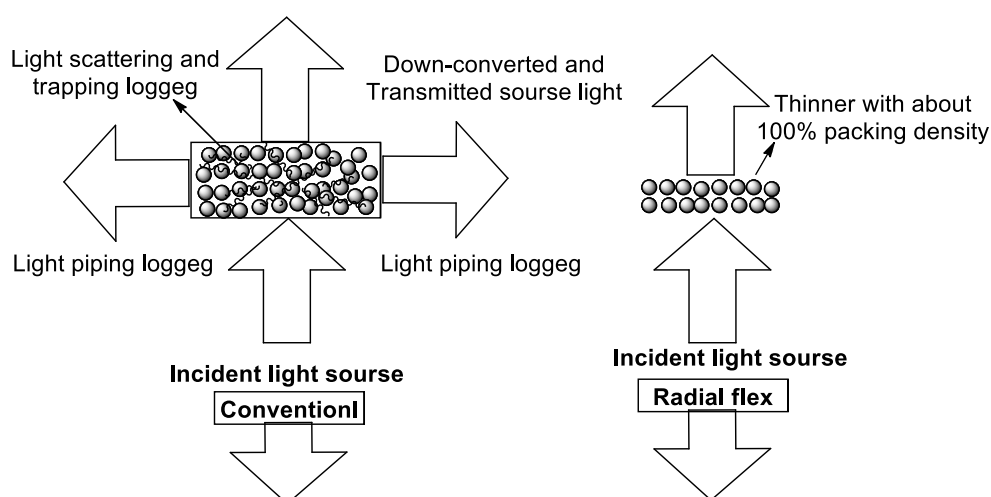


Figure 25. RGB phosphor sheets in SPE.

Due to their numerous benefits, self-powered UV photodetectors (Figure 26) based on TiO_2 and ZnO nanorod arrays have received a lot of interest in recent years. UV detectors based on photochemical cells have shown impressive results. However, liquid electrolytes are cumbersome for practical applications and are not appropriate for long-term operation. As a result, there is a pressing need to replace liquid electrolytes with solid-state hole transfer materials. We designed a unique nanostructured UV photodetector with an LC-embedded

quasi-solid-state electrolyte. The UV photodetector has a quick photoresponse speed and high photosensitivity due to the quasi-solid-state electrolyte's light-trapping method. The gadget could react quickly between "high" and "low" states with a big "on/off" ratio of three orders of magnitude and maintain good stability, thanks to the light on/off switching. These findings suggest that the quasi-solid-state UV photodetector could be utilized indefinitely for photoelectronic switching and high-sensitivity, fast UV light detection. Vertical rutile TiO₂ nanorod arrays produced on fluorine-doped tin oxide conductive glass served as the active photoanode. At 383 nm, a high incoming photon-to-current conversion efficiency of 29% was found, as well as a fast reaction time of less than 0.03 s [64].

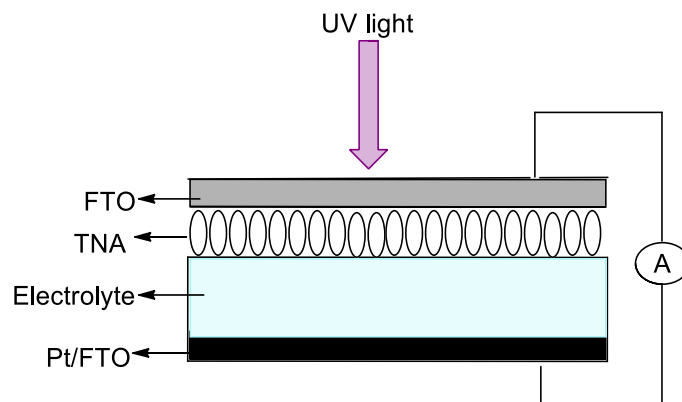
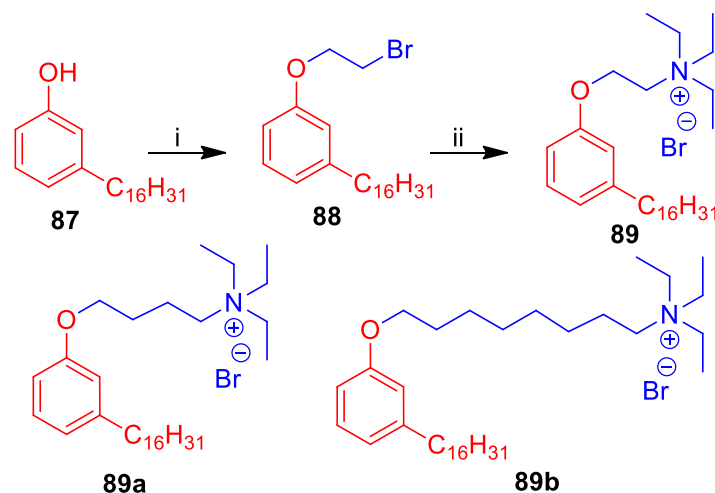


Figure 26. PEC-based UV photodetector.

LCD waste PCBs (Printed Circuit Boards) include important raw materials like tin, copper, and other precious metals. Electrowinning was used to achieve high-purity tin following suitable acid leaching of tin. The process parameters for leaching and electro-winning were adjusted for solution stability, dissolution, and electrolytic efficiency. Two aqueous electro-winning techniques were developed and proven on a mass-production scale: (1) As determined by the ICP (Inductively Coupled Plasma) technique, HCl leaching following preliminary HNO₃ dissolution was highly successful in leaching a large fraction of Sn. (2) Direct one-step leaching in H₂SiF₆ + H₂SO₄ + H₂O₂ was also tested, and the solution was eventually chosen as an electrolyte in electro-winning due to mass production capability. After 7 hours of electro-winning in aqueous H₂SiF₅ + H₂SO₄ + H₂O₂ at 40°C, the most effective tin recovery was observed: 96 % pure tin was recovered with a 93.2 % recovery rate [65].

Quaternary ammonium salts (QAS) are increasingly common in industrial applications because of their high surface activity, low aqueous toxicity, and resistance to oxidation and reduction. The anisotropic conduction mechanism has enabled the creation of QAS-based ionogels with a wider electrochemical window for use as electrolytes in solid-ion batteries and supercapacitors. Ionic liquid crystals fashioned on quaternary ammonium salts of 3-PDP with excellent purity and yield were assembled using a straightforward method (Figure 27). The production of crystalline, plastic crystalline, nematic, and hexagonal columnar phases was observed in amphotropic liquid crystalline phase transitions utilizing a variety of techniques. The origin of microscopic, rheological, and XRD research has been used to hypothesize the phase diagram and mechanism for the discovered LC and gel phases. The anisotropic ionic conductivity of $1.67 \times 10^{-2} \text{ Scm}^{-1}$, as determined by temperature- and concentration-dependent ionic conductivity studies, suggests that they might be used in high-energy instruments. In the LC phase of QSs, diffusion coefficient measurements confirm conductive paths. QS2 showed an excellent electrochemical window in electrochemical stability tests, indicating it could be

used as an electrolyte in supercapacitors. This is the most crucial assertion about the foundation of conductive liquid crystalline/gel, as it uses a low-cost, renewable source material derived from cardanol [66].



Reagents and conditions: (i) 1,2-Dibromoethane, KOH, 70 °C, (ii) TEA, methanol, 60 °C, 2 h, RT 1206 h.

Figure 27. SPE based on ionic liquid crystals fashioned on quaternary ammonium salts of 3-PDP.

Star-shaped polymers are created by atom transfer radical polymerization using poly(methoxy-poly (ethylene glycol) methacrylate) (PPEGMA) as a hydrophilic segment and poly10-[(4-cyano-40-biphenyl) oxy] decatyl methacrylate (PMALC) as a hydrophobic liquid crystalline segment (Figure 28). Cooperation between amorphous hydrophilic PPE and hydrophobic mesogen-containing polymethacrylates. Lamellar morphology can also result via GMA nanoscale aggregation, particularly after liquid crystal thermal annealing. Additionally, two different morphologies can be produced by sequential effects, or by changes in the location of the liquid crystalline segments in the copolymer electrolytes. Discontinuous molecular packing results from the mesogens' inability to interact properly with one another due to the liquid crystalline segments in the star polymer's inner sphere. But mesogens in the star copolymer exterior can create highly organized domains in the electrolytes, which can give a more favorable shape for ion transit. As a consequence, including liquid crystalline segments within the copolymer increased electrolyte ionic conductivity, particularly for the 3PPEGMA-PMALC with the mesogen on the exterior of the star copolymer sphere. A novel polymethacrylate liquid crystalline block copolymer with PEG and cyanobiphenyl side chains that is star-branched and amphiphilic is developed using a simple approach. LiClO₄ was added to 3PPEGMAPMALC and 3PMALC-PEGMA copolymers in various proportions to produce the copolymer electrolytes. Copolymer electrolytes have a structure that is quite different from other electrolytes. The same in the exterior sphere (3PPEGMA-PMALC) is associated with the LC segment organized in the star copolymer interior sphere (3PMALC-PPEGMA) and provides extra advantageous ion pathways for ion transference. The maximal room-temperature ionic conductivity for the 3PPEGMA-PMALC/LiClO₄ electrolyte with a [O]/[Li⁺] % of 20 after annealing is 1.0×10⁻⁴ Scm⁻¹. The polymer electrolytes (Figure 24) coalesce the LC group into a branched block structure, making them strong contenders for all-solid-state lithium-ion batteries [67].

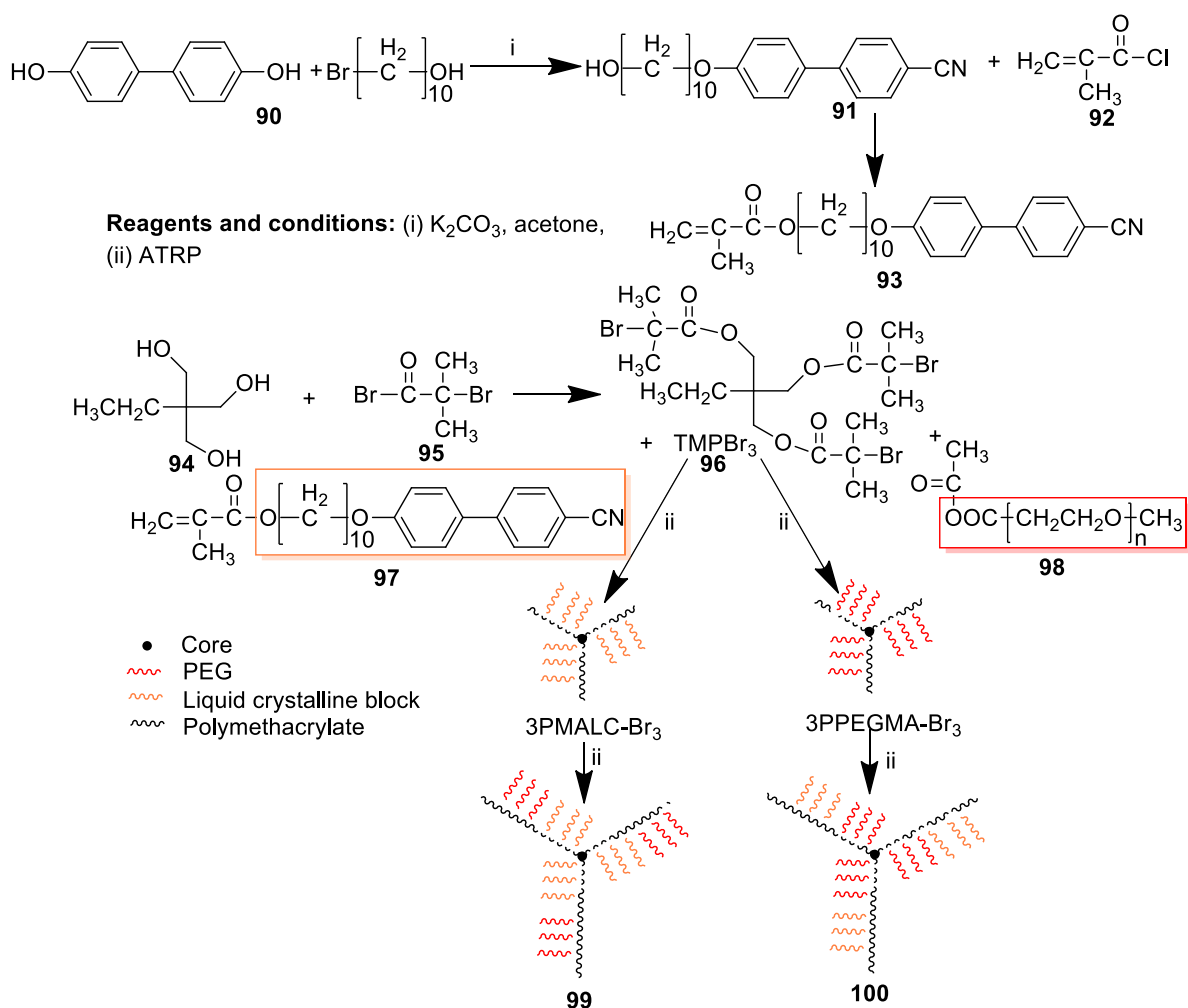


Figure 28. SPE with polymethacrylate liquid-crystalline block copolymers comprising PEG and cyanobiphenyl side chains.

In electrolysis of salt media, using liquid metal cathodes improves current efficiency, clearly separates the salt and metal phases, and achieves successful separation of components with similar characteristics. If solid phases form on the cathode surface during electrolysis, these benefits are not fully realized. It is vital to understand the regularities of solid-phase crystallization and their impact on the selectivity of electrochemical processes in order to minimize these undesired phenomena. The overpotential of solid-phase formation on liquid metal electrodes is systematically explored for various deposited metals, liquid metal cathodes, and emerging solid phases. The process of solid-phase nucleation on liquid-metal cathodes in the electrolysis of molten salts is firmly established in the executed study. It is predicted that nucleation would be limited. The present fraction contributing to solid-phase nucleation on the surface of a liquid-metal cathode is estimated using a methodology. It is 95–97 % of the current put in for phases in equilibrium with it; in the case of intermediate phases, it is fractions of a % or many %; and for the metallic uranium stage, it is 5–50 % of the current put in. The crystallization factors used to explain this condition agree well with results in the literature [68].

By atom-transfer radical polymerization, novel amphiphilic liquid crystalline (LC) copolymers with star branches, specifically 4-Arm poly(ethylene oxide)-co-x-[(4-cyano-4-biphenyl)oxy]alkyl methacrylate containing cyanobiphenyl mesogenic pendants (MAxLC), are created (ATRP). We investigate how structural differences affect copolymer electrolyte characteristics and the link between morphology and ionic conductivity. Even after doping with

LiClO_4 , the copolymers with an enantiotropic mesophase are induced by the robust assembly of cyanobiphenyl mesogens. Also, cooperative assembly of hydrophilic TPEO nanoscale aggregation and hydrophobic mesogen-containing polymethacrylate groups, particularly following LC thermal annealing, results in lamellar structures. The inclusion of cyanobiphenyl mesogens considerably increased the ionic conductivity. This is because mesogens not only promote ordered morphology to provide an effective ion-transport channel, but also reduce TPEO crystallization, allowing TPEO chain mobility.

A simple method is used to create a star-branched amphiphilic liquid crystalline block copolymer with four poly(ethylene oxide) arms and polymethacrylate with birefringent mesogens at the end of each component (Figure 29). The cyanobiphenyl mesogen imparts enantiotropic liquid crystalline optical anisotropy to copolymers and polymer electrolytes, resulting in lamellar formations. The amorphous, hydrophilic TPEO nanoscale accumulation and the cooperative assembly of hydrophobic mesogen-containing polymethacrylate groups validate the aligned nanostructures. A large number of LC groups and a large number of spacers necessitate an extra well-ordered filling technique. Ionic conductivity increases significantly when mesogen-hooked star-branched blocked polymers are combined, and this increase can be accelerated by thermal annealing from LC states. After annealing, the TPEO-MA9LC-19/ LiClO_4 electrolyte with a $[\text{O}]/[\text{Li}]$ ratio of 16 has a maximum room temperature ionic conductivity of $5.39 \times 10^{-5} \text{ S cm}^{-1}$. Although ionic conductivity does not meet the claim, combining the LC group with a branched block structure allows consideration of the relationship between morphology and ionic conductivity and offers a viable route for designing new high-ion-conducting organic materials [69].

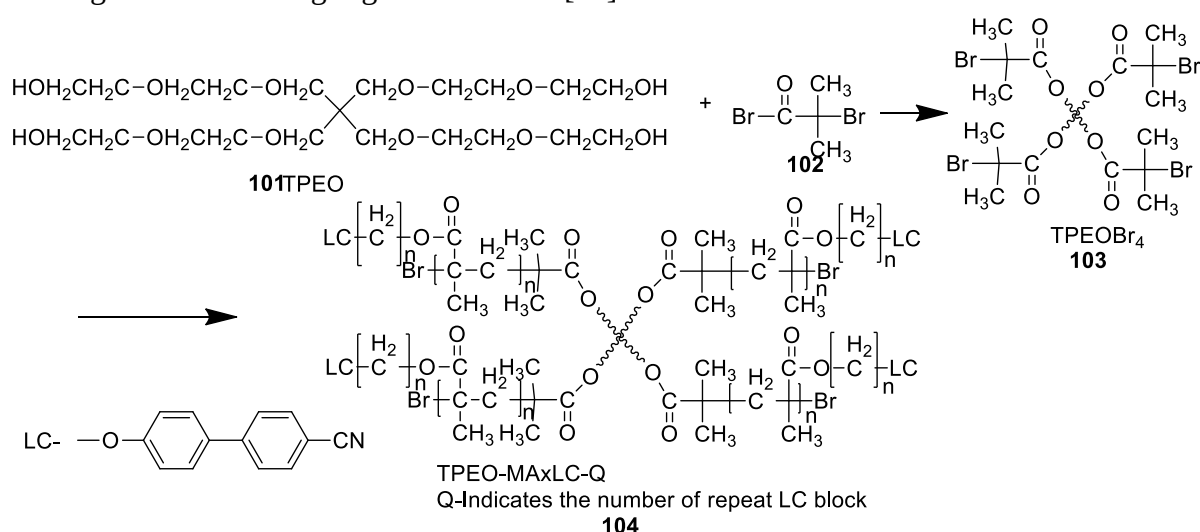


Figure 29. Liquid crystalline block copolymers comprising four poly(ethylene oxide) arms and polymethacrylate with birefringent mesogens.

If ultrasonic energy is applied to an NCC suspension former during film formation, the terrain of the chiral nematic phase in suspension rises, and the final iridescent film's reflection band shifts to stretched wavelengths (Figure 30). The energy contribution per gram of NCC in the sample controls the magnitude of the red shift in the reflection band. Sonication has a long-term and cumulative effect on treated NCC suspensions. NCC suspensions subjected to different amounts of sonication may have changed at the same time. As a function of the applied ultrasonic energy, the resulting film's conductivity and peak reflection wavelength for a 2.8 wt% NCC suspension develop. The cellulose nanocrystal is surrounded by a layer of water or a gel layer of sulfated oligosaccharides that contain ions formed during the hydrolysis

technique, which have not gone unnoticed during the purification processes. These ions form the electrical double layer and shelter the oligosaccharide moieties from electrostatic repulsions. Sonication releases specific ions into the bulk suspension, resulting in a thicker electrical double layer and weaker chiral relationships between units, or stronger repulsions bordered by oligosaccharides and oligosaccharide gel-layer inflammation. On the NCC facet, covalently bound sulfate ester groups and their proton counter ions, as well as the ion valencies, have gone astray in terms of accuracy. Nanocellulose film iridescence monitoring by using biomacromolecules and reflection wavelengths that adhere to a median measure of sonication, solid iridescent NCC films may be created. The addition of an electrolyte to the suspension upturns the effects of sonication, causing a blue shift in reflection wavelength. The sonication-induced red shift of NCC film iridescence may be electrostatic, with ions excluded from the leap-water layer or a gel layer of sulfated oligosaccharides at the NCC particle facet, according to increasing evidence. Additional NCC properties, such as particle length, cellulose chain DP, and surface charge density, are no longer emerging to support this conclusion [70].

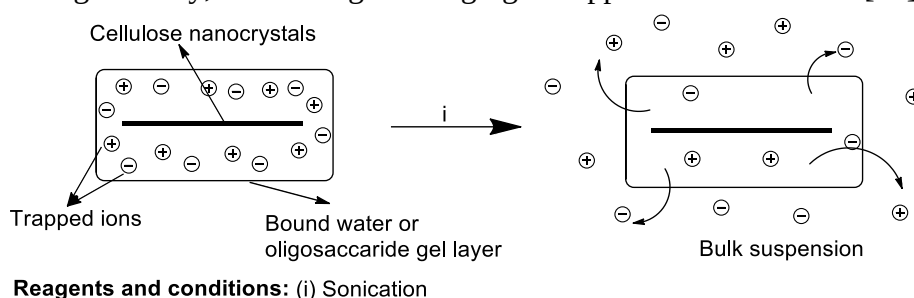


Figure 30. Sonication in bulk suspension- chiral nematic phase in suspension- changes the reflection band of the final iridescent film to stretched wavelengths.

A new discotic side group polymer based on a mainly poly(ethylene oxide) backbone to which triphenylene-based mesogenic groups are bonded through flexible spacers has been synthesized and characterized (Figure 31). Ion transport in this material is apparently aided by local backbone segmental movements but does not rely on long-range cooperative movements. The mechanical and thermal conductivity of the polymer TPC10G6 and its lithium perchlorate composite are identical. The glass transition temperature and clearing point of the host polymer were both enhanced as the salt accumulated. The temperature dependence of the polymer–salt complex's ionic conductivity is presented, revealing that ionic conduction may occur in essentially solid-like liquid crystal polymer electrolytes [71].

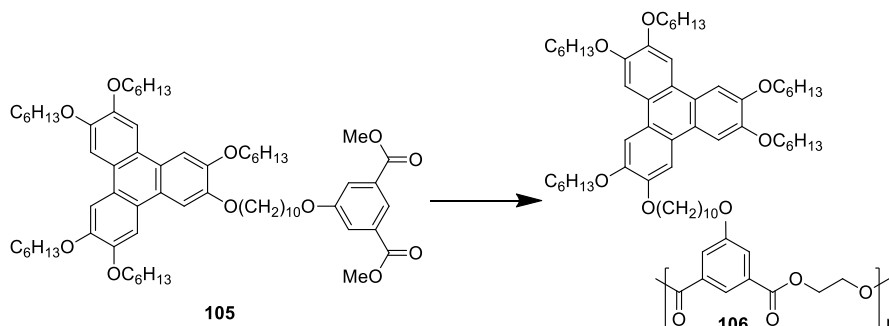


Figure 31. TPC10G6 with poly (ethylene oxide) support to which are affixed triphenylene-based mesogenic groups.

Because of its distinct features, liquid crystal polymer (LCP) offers a wide range of possible uses as a substrate material in electronic packaging. The work presented in this research was done to achieve LCP metallization for board manufacturing and to investigate the

adhesion between deposited copper and LCP. A copper deposition technique on LCP was developed, including chemical modification of the LCP exterior, Palladium catalyst activation, electroless deposition of 5 m copper, high-temperature treatment, and finally electroplating in a copper bath to increase the copper thickness to 40 m. The copper layer's adhesion strength on LCP is typically 54 g/mm, as determined in a cut-off study. Efforts were made to improve the copper's adhesion and strength properties on the LCP surface. Copper and LCP adhesion is thought to have mechanical and chemical origins, and an XPS analysis is underway. Extra effort is required to speed up the process and produce well-pitched structures immediately following electroless copper plating. This project establishes a source for additive metallization in ultra-fine line technology for micropatterning [72].

The ion that performs liquid crystalline schemes, such as TPEOCELL and LiCF₃SO₃ complexes, has been seen (Figure 32). The utmost conductivities shift to advanced salt concentrations as the temperature rises, with activation energies for ion transport in the range 53~73 kJ/ mol and a linear dependence of log s on 1/T. There were two types of morphological structures identified. Undoped TPEOCELL has chiral nematic order and an irregular, lamellar-like surface on its cracked exterior, whereas its LiCF₃SO₃ complex has a coarsened, array-like design that may relate to microphase-separated areas [73].

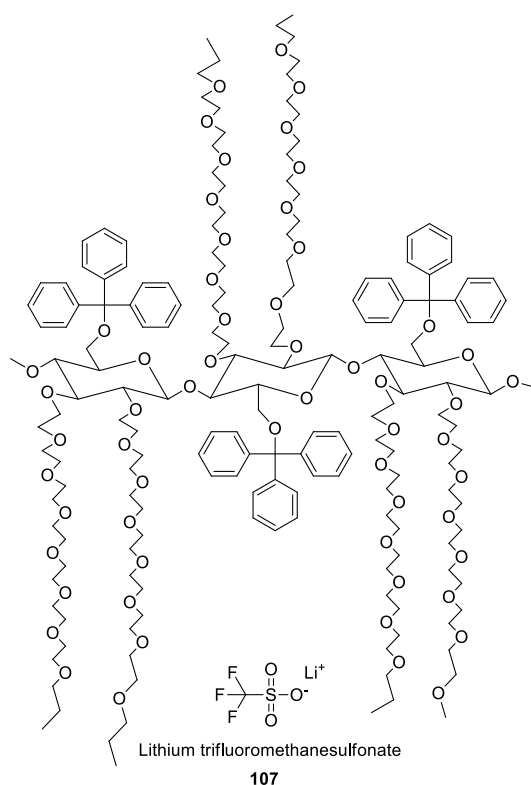


Figure 32. SPEs resulted from liquid crystalline schemes including TPEOCELL and LiCF₃SO₃.

Table 4. Highlights the key findings from the text about the solid polymer electrolytes (SPEs) and related materials for energy storage devices.

Year and author	Figure	Material	Key features	Performance metrics
2019 & Fisher S P <i>et al.</i>	Figure 18	Closo-carborane anions	Weakly coordinating anions; used as dianionic C σ-bound ligands for coordination and catalyst design.	Not provided; focus on versatility in catalytic and electrochemical applications.

Year and author	Figure	Material	Key features	Performance metrics
2019 & Wang C <i>et al.</i>	Figure 19	Gemini ammonium tetrafluoroborate liquid crystals	Cross-linkable ionic liquid crystals for ion conduction; anisotropic films formed by photopolymerization.	Ionic conductivity = 10^{-3} S/cm in the vertical direction at 180°C; anisotropy ratio = 100–350.
2018 & Zhang N <i>et al.</i>	Figure 20	PEO/PLA solid polymer electrolyte with LCI-MMT	Solution-blended solid polymer electrolyte; reduced crystallinity of PEO and increased crystallinity of PLA with LCI-MMT.	Ionic conductivity = 1.05×10^{-5} S/cm at room temperature with 0.5 wt% LCI-MMT.
2017 & Ito T <i>et al.</i>	Figure 21	MAImC1-PW12 inorganic-organic hybrid solid electrolyte	Hybrid monomer (MAImC1) with heteropolyanions (PW12); polymerized to form solid electrolytes.	Conductivity = 5.7×10^{-4} S/cm at 313K under humidified conditions.
2016 & Bui H T <i>et al.</i>	Figure 22	TPE derivatives with nonpolar dodecyl chains	Bulk TPE derivatives with nonpolar chains forming columnar LC phases; efficient aggregation-induced emission.	High AIE efficiency; conductivity varies with temperature and light exposure.
2016 & Zhang A L <i>et al.</i>	Figure 23	PEO/PMMA/LiClO ₄ solid polymer electrolyte with LCI	Solid polymer electrolyte doped with liquid crystalline ionomers (LCI); phase separation restrained with LCI.	Ionic conductivity = 2.53×10^{-4} S/cm at 1.0% LCI; enhanced by LiClO ₄ concentration.
2015 & Nardele C G <i>et al.</i>	Figure 24	Azobenzene LC polymers for solid electrolytes	Thermotropic azobenzene polymers with ionic conductivity; light-responsive materials for enhanced performance.	Ionic conductivity = 10^{-5} S/cm at 25°C, increases with temperature.
2014 & Menkara H <i>et al.</i>	Figure 25	RGB phosphor sheets for lighting and displays	Roll-to-roll production of flexible RGB phosphor sheets for high CRI and CCT in display applications.	Ultra-high CRI (>96) and CCT range from 2700 K to 8000 K.
2014 & Xie Y <i>et al.</i>	Figure 26	Quasi-solid-state UV photodetector with TiO ₂ and ZnO	UV photodetector using nanostructured TiO ₂ /ZnO arrays and LC-embedded quasi-solid-state electrolytes.	Photon-to-current conversion efficiency = 29%; fast response time (<0.03s).
2014 & Sasi R <i>et al.</i>	Figure 27	QAS-based ionogels for solid-state energy devices	Quaternary ammonium salt-based ionogels with anisotropic conduction properties; large electrochemical window.	Ionic conductivity = 1.67×10^{-2} S/cm; excellent electrochemical stability.
2014 & Tong Y <i>et al.</i>	Figure 28	Star-shaped polymers with PPEGMA and PMALC	Hydrophilic PPEGMA segment and hydrophobic PMALC segment; cooperative assembly resulting in lamellar morphology.	Ionic conductivity = 1.0×10^{-4} S/cm at room temperature for 3PPEGMA-PMALC/LiClO ₄ after annealing.
2014 & Tong Y <i>et al.</i>	Figure 29	Star-branched amphiphilic liquid crystalline block copolymer with four PEO arms	Four poly(ethylene oxide) arms with cyanobiphenyl mesogens; enantiotropic liquid crystalline optical anisotropy.	Ionic conductivity = 5.39×10^{-5} S/cm for TPEO-MA9LC-19/LiClO ₄ after annealing with [O]/[Li] ratio of 16.
2011 & Beck S <i>et al.</i>	Figure 30	NCC suspension under sonication	Chiral nematic phase changes in suspension under sonication; reflection wavelength shift to stretched wavelengths.	Blue shift in reflection wavelength with electrolyte addition; detailed electrostatic effects on NCC properties.
2004 & Imrie C T <i>et al.</i>	Figure 31	Discotic side group polymer with PEO backbone and triphenylene-based mesogens	Triphenylene-based mesogens bonded to the PEO backbone; local segmental movements aid ion transport.	Identical mechanical and thermal conductivity for TPC10G6 and its LiClO ₄ composite.

Year and author	Figure	Material	Key features	Performance metrics
2002 & Yue Z <i>et al.</i>	Figure 32	TPEOCELL and LiCF ₃ SO ₃ complexes	Ion-based liquid crystalline schemes; two distinct morphological structures: chiral nematic and array-like designs.	Activation energy for ion transport: 53-73 kJ/mol; ionic conductivity shifts with salt concentration and temperature.

This table summarizes the essential details of each SPE material, including composition, unique features, and performance metrics for energy storage device applications.

10. Conclusion

Ionic Liquid Crystals, which combine the distinctive properties of liquid crystals and ionic liquids, offer exceptional tunability in phase behavior, mesomorphic properties, and physicochemical characteristics. By designing diverse cationic and anionic components, researchers can explore novel structures with tailored functionalities, enabling precise control over ionic conductivity, phase transitions, and interfacial interactions. While significant progress has been made in developing new mesophases, practical deployment in devices such as dye-sensitized solar cells and solid-state electrolytes remains limited by challenges including mechanical stability, interfacial compatibility, and scalable fabrication. Ongoing research focused on optimizing molecular architecture, enhancing device integration, and leveraging light- and ion-management strategies positions ILCs as a transformative platform for next-generation energy, optoelectronic, and advanced materials technologies. With continued exploration of their tunability and application-specific design, ILCs are poised to bridge fundamental science and industrial innovation, offering new opportunities for high-performance, durable, and versatile energy devices.

Author Contributions

Conceptualization, C.M.; investigation, C.M.; resources, C.M.; data curation, C.M.; writing—original draft preparation, C.M.; writing—review and editing, V.B. and S.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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