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The Role of Hexagonal Boron Nitride (h-BN) in Enhancing Electrolytes for Safer and Efficient Lithium-Based Batteries

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Hexagonal boron nitride (h-BN), with its unique structural and thermal properties, has emerged as a versatile material capable of addressing challenges such as thermal instability, dendrite formation, and limited ionic conductivity across liquid, gel polymer, and solid-state electrolytes (SSEs) for high-performing lithium ion and lithium metal batteries (LMBs). In liquid electrolytes, h-BN improves ionic mobility and suppresses side reactions, while in gel polymer electrolytes (GPEs), it enhances mechanical flexibility and thermal stability. SSEs benefit from h-BN's ability to suppress dendrites, reinforce mechanical strength, and optimize interfacial compatibility, making it a key enabler for next-generation battery technologies. Despite its promise, challenges such as dispersion uniformity, cost, and interfacial complexity must be addressed. Future directions, including the development of multifunctional architectures, dynamic electrolytes, and sustainable synthesis methods, are discussed to guide the integration of h-BN in emerging energy storage systems. This perspective article explores the multifunctional roles of h-BN, highlighting its contributions to enhancing ionic transport, thermal management, and interfacial stability. By presenting a comprehensive overview of h-BN's role in electrolytes, this work aims to inspire further research into its potential to revolutionize energy storage technologies.

1. Introduction

Electrolyte is a fundamental component in batteries, serving as the medium for ion transport between electrodes during cycling. The performance, stability, and safety of batteries are heavily influenced by the design of electrolytes.[1] With the ever-increasing demand for efficient and durable energy storage solutions for electric vehicles (EVs), portable electronics, and grid-scale storage, researchers have focused on formulating electrolyte systems that offer improved ionic conductivity, broader electrochemical stability window (ESW), advanced thermal management, safe-by-design, and enhanced mechanical properties.[2,3]

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The progress in Li-ion batteries (LIBs) necessitates addressing several critical challenges encompassing poor thermal stability, anode/electrolyte interface incompatibility, and low ionic conductivity in electrolytes. Also, the mechanical robustness of electrolytes is required to prevent dendrite growth, which can lead to battery failures and thermal runaway.[4] h-BN, a 2D material, has recently demonstrated the potential to address these critical challenges for enhancing electrolyte's thermal, mechanical, and electrochemical behavior.[5] h-BN's advances in energy storage systems have also seen significant expansion, attributed to its tunable electronic properties through surface functionalization, particularly in comparison to other 2D materials (**Figure 1**).[6]

h-BN is typically synthesized using several methods such as chemical vapor deposition (CVD), exfoliation of bulk h-BN, and bottom-up chemical synthesis.[7–9] Among these, CVD is particularly noteworthy for its ability to produce high-purity, large-area monolayers, while exfoliation techniques are favored for obtaining multilayered structures from bulk crystals. Additionally, recent advances in chemical synthesis methods have enabled the scalable production of functionalized h-BN with tailored properties for specific applications.[10–16]

The electrochemical stability of h-BN makes it an ideal candidate for mitigating side reactions and mechanical degradation.[17] For example, as a surface coating, h-BN effectively suppresses dendrite growth by regulating ion flux.[18] Notably, h-BN can create energy barriers to inhibit electron tunneling, thereby effectively preventing the decomposition of the electrolyte.[19] Furthermore, the 2D morphology of h-BN provides a platform for controlled ionic transport by reducing concentration polarization, while its chemical inertness helps prevent side reactions and improves long-term stability.[20,21]

This review aims to fill critical gaps in the existing literature by providing a comprehensive analysis of h-BN across all major electrolyte systems, including liquid, gel polymer, and solid-state

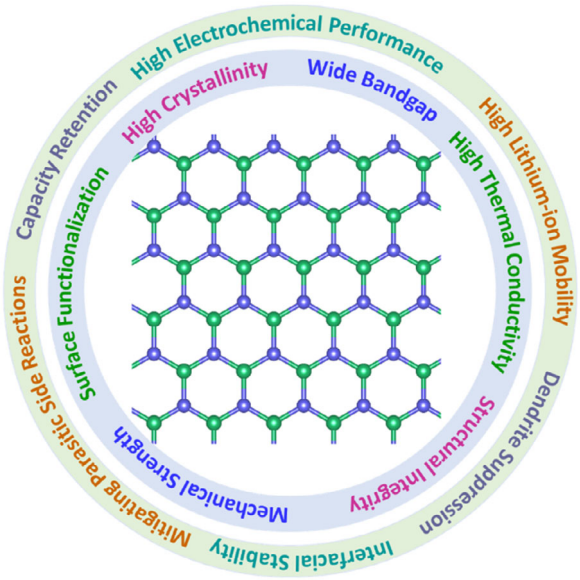
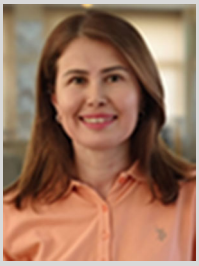


Figure 1. Advantages of h-BN for lithium-based electrolytes.

electrolytes.[5,22,23] Unlike previous reviews that predominantly focus on h-BN's role in solid-state systems or as an electrode additive, this work presents a unified perspective that highlights its multifaceted applications in LIBs. Special emphasis is placed on the mechanisms by which h-BN enhances ionic conductivity, suppresses dendrite formation, and improves thermal stability, providing perspectives for advancing electrolyte design. Furthermore, this review explores h-BN's potential to address challenges associated with high-voltage operations, such as oxidative stability and interfacial degradation—areas that are often overlooked in the existing literature. Finally, we outline future opportunities for h-BN in emerging battery chemistries and discuss practical challenges, including material scalability and processing, to guide the next steps in this field.

2. Hexagonal Boron Nitride: Structural and Chemical Properties

Bulk h-BN consists of layered sheets that are hexagonally arranged and bonded through sp^2 hybridization, where B and N atoms have trigonal planar configurations.[22,24] It comprises two atoms with disparate electronegativity (boron = 2.04, nitrogen = 3.04), imparting an ionic character to the material, resulting in its electron-insulating properties.[18,25] The high thermal conductivity of h-BN (2000 $W m^{-1}K^{-1}$) can be attributed to its wide bandgap (5–6 eV) and stable crystallinity, withstanding temperatures of up to 1000 °C in the air.[26,27] h-BN nanosheets (h-BNNSs) exhibit remarkable mechanical properties, characterized by Young's modulus of 0.8 TPa and an elastic modulus of 510 $N m^{-1}$, providing high flexibility and stretchability.[28–30]



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The addition of h-BN nanosheets (h-BNNSs) to solid-state electrolytes (SSEs) has the potential to improve ionic conductivity, inhibit the formation of lithium dendrites, and mitigate the risks associated with thermal runaway. The low electrical conductivity of h-BN plays a crucial role in facilitating these enhancements, establishing it as a significant additive in battery technologies.[31]

The inert surface chemistry of h-BN contributes to its chemical stability in harsh environments, such as those encountered in electrochemical systems. While this inertness is a strength, it can also limit interactions with electrolyte components.[18] To overcome this, surface functionalization of h-BNNSs can improve compatibility with various electrolyte matrices (**Figure 2**a).[28] As an example of utilizing covalently functionalized h-BNNS, hydroxyl[32] or amine groups[33,34] can be introduced onto h-BNNS surfaces to enhance interaction with polymer matrices in gel polymer electrolytes (GPEs) and to promote ionic conductivity in solid-state systems (Figure 2b). Functionalized h-BNNS can also serve as a host for ionic liquids or salts, creating hybrid materials with enhanced electrochemical properties (Figure 2c–e).[28–30,32] Moreover, like graphene, BNNS features π conjugation, which allows for π–π stacking interactions with other molecules that possess benzene rings or similar conjugated units. In contrast to carbon allotropes, the boron–nitride bond exhibits properties similar to ionic bonds, resulting in a natural electronic polarity. Thus, the Lewis acid–base principle can be applied to enhance electronegativity through the attraction of positive and negative charges, facilitating noncovalent interactions. Furthermore, other noncovalent interactions, including hydrogen bonding, electrostatic interactions, and the introduction of defects, can also be utilized to alter the surface characteristics of BNNS, improving its solubility and compatibility. Among these strategies, π–π stacking, especially with molecules that have a benzene ring affinity, is the most prevalent approach for the functionalization of BNNS.[35–37]

3. Current Status of h-BN in Li-Based Electrolytes

h-BN's inclusion in electrolytes offers several performance benefits. A comparison table showing the effects of h-BN incorporation on electrochemical properties is provided in **Table 1**. For example, the incorporation of h-BNNSs significantly enhances the mechanical properties of GPEs. This enhancement occurs while maintaining a high ionic conductivity at room temperature in contrast to traditional bulk h-BN microparticles.[18,38] h-BNNSs demonstrate compatibility with high-voltage cathodes (greater than 5 V versus Li/Li^+) and provide remarkable thermal stability, enabling the operation of solid-state LIBs at elevated temperatures, reaching up to 175 °C (**Figure 3**e,f).[38] Moreover, many studies have emphasized that B atoms in BN, having Lewis acidity, hold the anions in the electrolyte, resulting in the fast Li^+ movement due to the interaction between Li^+ ions and h-BN nanoflakes.[30,39,40] For example, Zhao et al. reported that $TFSI^-$ anions were trapped by the B atoms within h-BN, and the selective Li-ion transport was improved in the solid polymer electrolyte (SPE).[39]

The high thermal conductivity and stability of h-BN make it an excellent choice for improving the heat tolerance of electrolytes, a critical requirement in high-power applications such as electric vehicles.[41–43] For example, in a composite bilayer separator, the addition of h-BN particles to polyethylene (PE) matrix significantly enhances the interfacial interactions between the PE and poly(vinylidene fluoride-hexafluoropropylene) (PVDF-HFP) layers, thereby preventing layer separation and reducing dendrite growth as compared to Celgard 2325. This bilayer separator achieves an impressive electrolyte uptake of 348% and exhibits a thermal shrinkage of 6.6% after annealing at 140 °C for 1 h (Figure 3a–d).[44] When integrated into GPEs and SPEs, h-BN enhances mechanical integrity, reducing the risk of dendrite formation and electrolyte breakdown. Yin et al. introduced 2D h-BN

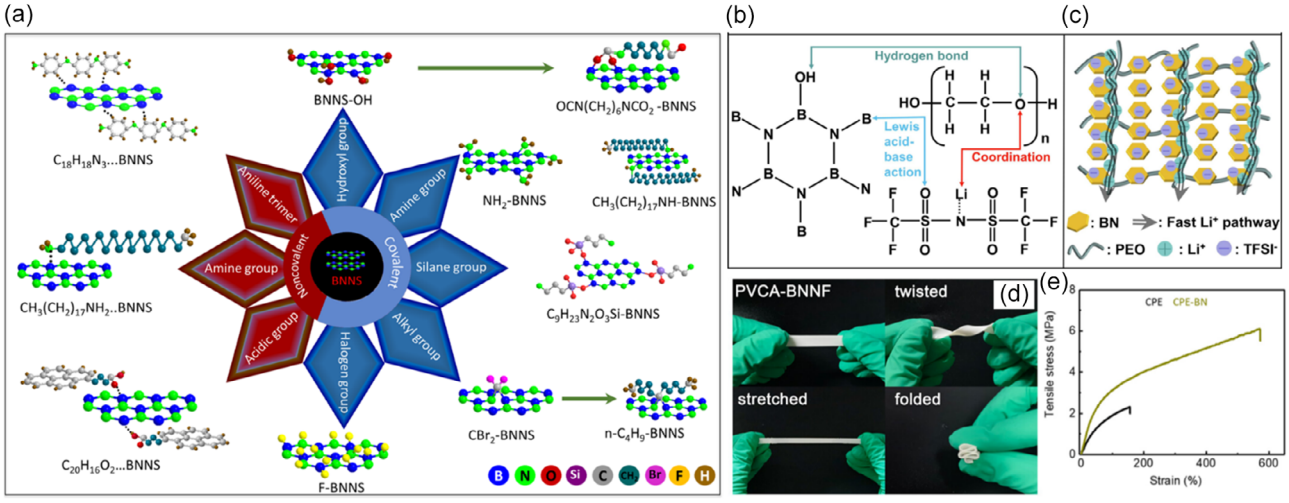

Figure 2. a) Covalent and noncovalent functionalization of h-BNNSs with various functional groups. Adapted with permission.[28] Copyright 2021, from Nature Publishing Group. b) The interactions between PEO/LiTFSI and the BN nanosheets. c) The structure of the CPE. Adapted with permission.[32] Copyright 2024, Elsevier B.V. d) PVCA-BNNF QSSE being twisted, stretched, and folded. Adapted with permission.[30] Copyright 2023, American Chemical Society. e) Stress–strain test results of the CPE and CPE-BN. Adapted with permission.[29] Copyright 2022, American Chemical Society.

Table 1. The performance comparison of h-BN-containing electrolytes for Li-based batteries.

Electrolyte[a)]	Ionic conductivity [mS cm^{-1}] at RT	ESW (vs Li/Li$^+$)	^{t}Li$^+$	C-rate, capacity retention	Ref.
h-BN nanoplates/LiTFSI/EMIM-TFSI	1	5 V	0.18	1C, 100 cycles with 90% capacity retention at 175 °C.	[38]
h-BN/LiTFSI/PP13	3	5.4 V	0.093	3C, 500 cycles, with 97%, capacity retention at 120 °C	[41]
h-BNNS/LATP/PVDF-HFP/ LiTFSI/ PYR_{13} TFSI/pDOL	0.149	5 V	0.65	845.6 mAh g^{-1} at 0.2 C, 100 cycles with 81.2% capacity retention at RT.	[48]
h-BN/PVDF-HFP/LiTFSI/[EMIM][TFSI]	0.916	5 V	0.641	155.7 mAh g^{-1} at 0.2C, 300 cycles, with a capacity retention of 82.2% after 300 cycles	[56]
BNNs-MPS-PEGDA	0.1	5.5 V	0.49	125 mAh g^{-1} at 0.5C, 600 cycles, with capacity retention of 80% at RT.	[61]

[a)]PP13: 1-methyl-1-propylpiperidinium bis(trifl uoromethylsulfonyl)imide; PYR_{13} TFSI: N-propyl-N-methylpyrrolidinium bis(trifluoromethanesulfonyl)imide; [EMIM][TFSI]: 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide; LiTFSI: lithiumbis(trifluoromethylsulfonyl)imide; PVDF-HFP: poly(vinylidene fluoride-*co*-hexafluoropropylene); LATP: $Li_{1.5}Al_{0.5}Ti_{1.5}(PO_4)_3$; pDOL: poly(1,3-dioxolane; RT: room temperature; NhBN: nanostructured hexagonal boron nitride; PEGDA: polyethyleneglycol diacrylate; MPS, 3-(methacryloyloxy)propyltrimethylsiloxane.

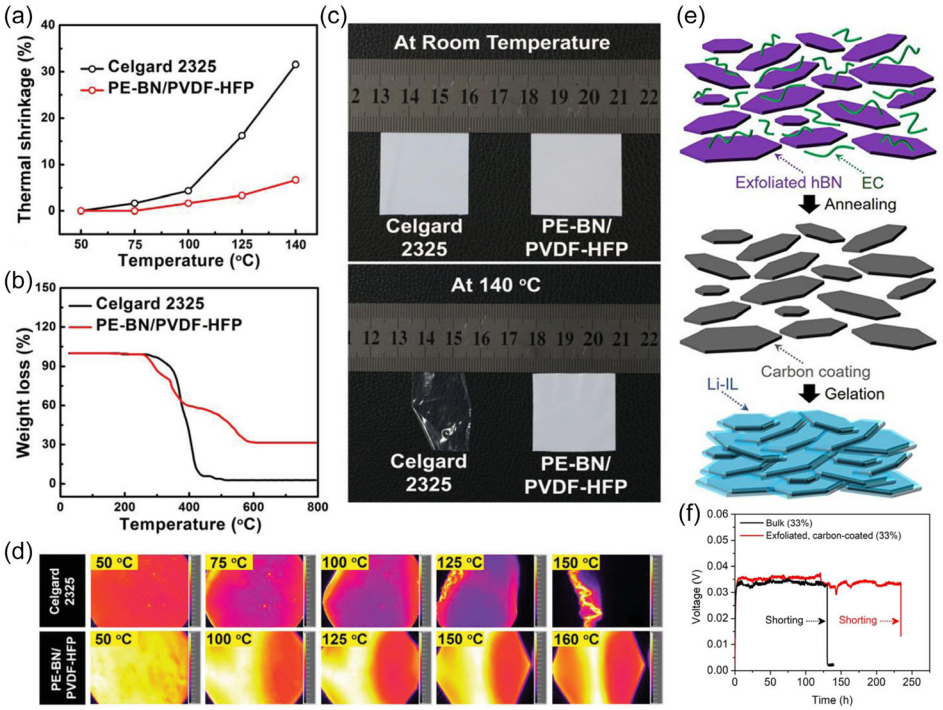

Figure 3. a) Thermal shrinkage of the separators, b) TGA results of the separators, c) digital images of the separators before and after heating (at 140 °C for 1 h), and d) FLIR images of the separators. Adapted with permission.[44] Copyright 2019, Wiley-VCH. e) Schematic diagram of h-BN gel electrolyte preparation. f) Polarization voltage profiles of symmetrical cells (Li|gel electrolyte|Li) with gel electrolytes. Adapted with permission.[38] Copyright 2019, American Chemical Society.

nanoflakes into a polyethylene oxide (PEO)-PVDF blended polymer electrolyte to form a solid-state composite electrolyte, improving the ionic and mechanical properties and promoting the electrolyte's thermal resistance.[45]

The interfacial compatibility between h-BNNSs and the polymer matrix is essential for transferring mechanical stress, thermal energy, and electrical characteristics across different phases. This can be achieved by functionalizing h-BNNSs for establishing covalent and noncovalent interactions, including hydrogen bonding, van der Waals forces, and π–π stacking between BNNSs and polymers.[46,47] Optimizing the distribution of h-BN in electrolytes provides innovative solutions to counteract performance issues related to localized hotspots and safety concerns. As an example of interfacial compatibility, a printable, thermally conductive composite polymer electrolyte (CPE), formulated from PEO and featuring well-aligned silane functionalized h-BN (S-hBN), represents a 1.7-fold increase in thermal conductivity and the storage modulus by 3–4 orders of magnitude compared to CPE that incorporate randomly distributed S-h-BN nanoplates.[43]

These features make h-BN versatile for advancing electrolyte performance across various energy storage technologies. Its ability to synergistically enhance ionic, thermal, and mechanical properties provides a foundation for innovation in next-generation electrolyte design.

3.1. Liquid Electrolytes

Liquid electrolytes are widely used in battery systems due to their high ionic conductivity and ease of processing. However, challenges such as flammability and susceptibility to side reactions persist. The incorporation of h-BN into liquid electrolytes offers promising solutions to these issues by leveraging its unique structural and chemical properties. h-BN typically functions as an additive to enhance stability and performance.[17,41] Its 2D layered structure provides a physical barrier inhibiting dendrite growth. Additionally, h-BN's thermal conductivity helps dissipate heat generated during high-rate cycling, reducing the risk of thermal runaway.[17,41]

Narrow ESW of liquid electrolytes also restricts their use in high-voltage systems, and the integration of h-BN can extend ESW, making h-BN-enhanced electrolytes suitable for next-generation batteries, such as lithium–sulfur (Li–S) and LMBs, which operate at higher voltages.[21] Rodrigues et al. formulated a composite electrolyte from h-BN and 1 M LiTFSI solution in a piperidinium-based room temperature ionic liquid, achieving an ESW up to 5 V and a broadened operational temperature range up to 150 °C.[41] In Li-S batteries, incorporating h-BNNS as a leveling agent into the traditional 1,2-dimethoxyethane/1,3-dioxolane (DOL/DME) electrolyte prevents dendrite formation during cycling. The presence of h-BNNSs in the electrolyte significantly enhances the transport of lithium ion (t_{Li^+}) relative to the blank electrolyte, which exhibits a t_{Li^+} value of 0.47. For an electrolyte containing 7 mg mL^{-1} of h-BNNSs, the t_{Li^+} value is recorded at 0.55.[17] These applications highlight the versatility of h-BN in addressing the limitations of liquid electrolytes across diverse energy storage systems.

3.2. Gel Polymer Electrolytes

GPEs combine the advantages of liquid and solid-state electrolytes by offering high ionic conductivity and flexibility.[6] However, challenges such as limited thermal stability, mechanical integrity, and long-term durability remain barriers to their commercialization.[5] Incorporating h-BN into GPEs forms an interfacial network that reinforces the gel structure, preventing deformation or collapse during operation.[20] Furthermore, the high aspect ratio of h-BNNSs facilitates continuous ion-conducting pathways, maintaining ionic mobility even under mechanical stress, making h-BN-enhanced GPEs suitable for flexible and wearable energy storage devices.[4] As a heat dissipation agent, h-BN prevents the electrolyte from overheating during high-rate cycling.[18,25] Moreover, the chemical inertness of h-BN reduces the likelihood of side reactions between the polymer matrix and electrolyte salts, extending the electrochemical stability window of the GPE. This makes h-BN-enhanced GPEs more compatible with high-voltage LMBs.[47]

Recent studies have demonstrated that GPEs containing h-BN exhibited enhanced ionic conductivity and suppressed lithium dendrite growth, leading to longer cycle life.[39] Kim et al. have recently designed an inorganic-gel hybrid electrolyte (IGHE) composed of inorganic $Li_{1.5}Al_{0.5}Ti_{1.5}(PO_4)_3$ (LATP), h-BNNSs, N-propyl-N-methylpyrrolidinium bis(trifluoromethanesulfonyl)imide, and

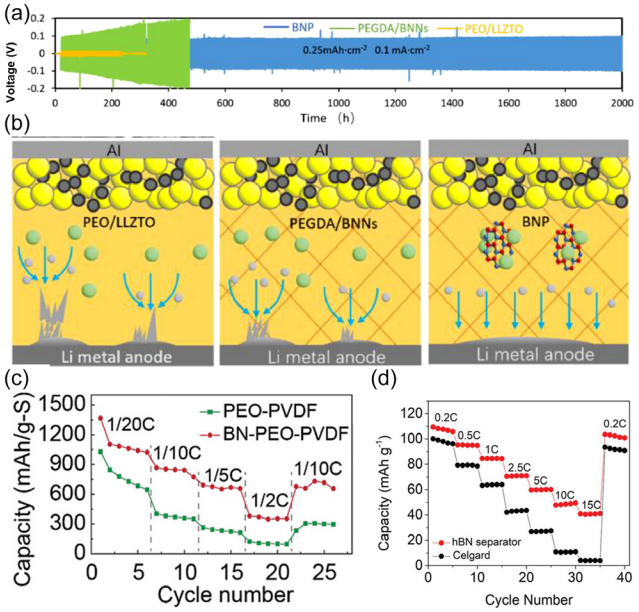

Figure 4. a) Long cycle performance of Li|Li symmetrical cells with different electrolytes. b) Schematic illustration of dendrite growth mechanism. Adapted with permission.[61] Copyright 2021,Elsevier B.V. c) Rate performance of the Li–S cells with BN-PEO-PVDF and PEO-PVDF electrolytes. Adapted with permission.[45] Copyright 2020, Wiley-VCH. d) Rate capability measurements using full device. Adapted with permission.[49] Copyright 2019, Wiley-VCH.

PVDF-HFP. LATP and h-BNNSs synergistically provided high Li^+ ion conduction in the IGHE.[48] h-BNNSs produced via polymer-assisted exfoliation technique allow the formulation of a printable ink with adjustable viscosity, and the GPE fabricated shows superior rate capability at all current rates from 0.2C to 15C in comparison to commercial Celgard separator (**Figure 4**d).[49] These findings underscore the multifunctional role of h-BN in improving both the structural and electrochemical properties of GPEs.

3.3. Solid-State Electrolytes

SSEs are considered cornerstones for next-generation energy storage technologies due to their potential to overcome safety and stability limitations associated with liquid electrolytes.[50,51] h-BN has emerged as a multifunctional additive and structural modifier capable of addressing these limitations.[47] Besides safety, the research interest has significantly intensified, concentrating on two critical aspects: high energy density and rate capability. This shift has led to the exploration of advanced SPEs.[52] Commonly used polymer matrices in SPEs include PEO, PVDF, and PVDF-HFP.[40] By employing strategies such as functionalizing polymer chains with anion acceptors and incorporating inorganic fillers, a high Li^+ diffusion is attained by Lewis acid–base pairs.[53] However, challenges such as low ionic conductivity, poor interfacial compatibility, and mechanical brittleness persist.[50] Poor interfacial compatibility often leads to high resistance and reduced efficiency. As an effective interfacial material, h-BN forms a physical barrier that inhibits dendrite penetration into the electrolyte. Its chemical inertness also reduces side reactions

at the interface, further stabilizing the system. When incorporated into SSEs, h-BN enhances the dispersion of ionic species and reduces ion aggregation, improving the overall ionic conductivity.[54] Moreover, h-BN helps to distribute mechanical stress evenly across the interface, preventing localized failures. Zhao et al. reported PVDF-based SSE with h-BNNSs, demonstrating remarkable electrochemical performance regarding fast ion transport and inhibition of dendrite growth. The optimized SSE (PVDF-L70-B5) provided a t_{Li^+} of 0.62, a high ionic conductivity of 2.98×10^{-4} S cm^{-1}, a substantial ESW of 5.24 V, and remarkable mechanical strength of 3.45 MPa.[39] h-BN's compatibility with various solid matrices, including ceramic and polymer-based SSEs, enables the creation of composite architectures that optimize ionic pathways.[45] Zhang et al. reported that PEO/LiTFSI/SiO_2@BNNS (PLSB) composite electrolyte in Li/$LiFePO_4$ battery cycled at ≈150 °C and demonstrated stable performance for over 1000 cycles at 2C.[55] Utilizing h-BNNSs as fillers in polymer matrices provides refined control over the surface and interface layers by reducing interfacial resistance. Rasul et al. show that BN-embedded PVdF SPE (CPE-BN) performed over 2000 cycles without short-circuiting, yielding an LMB with high C-rate cycling as a result of improved mechanical strength.[29] Also, Zhang et. al demonstrated an optimized SPE with composition of nanostructured h-BN/PVDF-HFP/LiTFSI/[EMIM][TFSI] having impressive ionic conductivity at 0.916 mS cm^{-1} at 25 °C, along with an improved Li-ion transference number of 0.641, wide electrochemical stability (>5 V versus Li/Li$^+$), and remarkable Li interfacial stability over 700 h, with a low overpotential of 20 mV at 0.1 mA cm^{-2}, reflecting its excellent ability to inhibit the formation of Li dendrites.[56]

The high aspect ratio of h-BNNSs reinforces the solid matrix, preventing cracking and delamination during repeated charge/discharge cycles.[57,58] Ma et al. demonstrate that 5 wt% of h-BN in PEO-based electrolytes improves ionic conductivity and mechanical strength. The utilized electrolyte provides 300 h of stable cycles in the symmetrical Li//Li cell at 0.1 mA cm^{-2} and had 89% capacity retention (138.9 mAh g^{-1} at 1.0 C) after 100 cycles with LFP cathode.[59] In another study, Meng et al. report that BN/PEO-LiTFSI CPE enhances the ionic conductivity and t_{Li^+}, 4 and 2 times higher than the pristine electrolyte.[32] Furthermore, Li et al. fabricated an SPE consisting of PEO and h-BN, resulting in considerable mechanical strength. Incorporating h-BN leads to improvements in ESW and t_{Li^+}; however, it concurrently reduces ionic conductivity within the h-BN composite electrolyte.[60] Due to h-BN's anion receptor function, the h-BN-embedded SPE demonstrates superior Li$^+$ conductivity but reduced anion diffusivity compared to the SPE without h-BN.[60] As an example of in situ polymerized nanohybrid electrolyte, An et al. synthesized an interpenetrating polymer network electrolyte through the chemical grafting of h-BNNS with poly(ethylene glycol) diacrylate (PEGDA) using a silane coupling agent. In situ polymerization of a surface functionalized h-BNNS as the active monomer markedly enhances the mechanical characteristics of the electrolytes at the molecular level, achieving a notable tensile strength beyond 25 MPa and elastic modulus >6.5 GPa, which effectively mitigates the dendrite formation. Additionally, the composite SPE demonstrates improved ionic conductivity (0.1 mS cm^{-1}) and t_{Li^+} (0.49). Also, symmetrical cells with SPE demonstrate remarkable stability over 2000 h, while full cells maintain high-capacity retention (Figure 4a,b).[61] The addition of BN also enhances the ionic and mechanical properties of the PEO-based SSE employed in Li-S batteries. The BN-PEO-PVDF cell demonstrates superior performance, exhibiting impressive capacities of 750 mAh g^{-1} at a rate of 0.2 C and 400 mAh g^{-1} at 0.5 C, whereas the PEO-PVDF cell yields only 300 mAh g^{-1} at 0.2 C and shows an insignificant capacity at 0.5 C (Figure 4c).[45]

4. Challenges

Despite significant advancements in the application of h-BN across various electrolyte systems, several challenges remain, such as dispersibility, cost, and interfacial complexity.[18] Addressing these challenges will unlock the full potential of h-BN-enhanced electrolytes in commercial energy storage technologies. The tendency of h-BN nanosheets to aggregate can compromise the uniformity of ionic pathways and mechanical reinforcement. Functionalization strategies, such as introducing polar groups or utilizing surface coatings, can improve compatibility with the polymer matrix. Developing scalable dispersion techniques and employing surface functionalization strategies are critical to overcoming this limitation.[57] Also, by taking advantage of the high thermal stability of h-BN, one-pot solvent-free processing techniques such as hot-melt extrusion can be used to fabricate high-performance SSEs. Consequently, further innovations in h-BN-polymer nanocomposites are essential to effectively harness the superior material characteristics of BNNSs in polymer applications.[28,46]

The utilization of dynamic covalent networks in recycling also presents considerable advantages, such as self-healing ability. Nonetheless, it also introduces technical challenges related to energy demands, processing times, material limitations, and potential environmental effects. It is essential to carefully assess and manage these disadvantages to optimize the recycling methodology.[62]

In solid-state and gel electrolytes, ensuring strong and stable interfacial contact while maintaining low resistance and high ionic mobility requires further refinement and innovation. Balancing the tradeoffs between enhanced interaction and preserved properties is a complex task that requires further investigation. In addition, the cost of synthesizing and functionalizing h-BN remains a barrier to large-scale adoption. There are only a few studies about biomass-based synthesis of h-BN. Wang et al. developed a robust and efficient method for the onsite synthesis of BN nanosheets with high crystal quality, utilizing biomass as a precursor.[63] Deshmukh et al. reported an innovative and environmentally friendly technique for producing hexagonal boron nitride nanosheets (h-BNNs) through ultrasound-assisted exfoliation of h-BN employing different plant extracts.[64] However, the use of biomass-derived precursors for the synthesis of h-BN poses numerous challenges due to the complex nature of biomass materials and the rigorous conditions necessary for h-BN formation.[65] Thus, developing scalable and cost-effective synthesis methods, such as biomass-derived precursors or simplified chemical routes, is essential

for commercialization.[50] Implementing more sustainable materials and processes represents a significant step forward, as it establishes improved recycling strategies and enhances the life cycle of batteries in alignment with the principles of a circular economy.

5. Summary and Outlook

h-BN has emerged as a transformative material in the realm of energy storage, offering unique advantages across liquid, gel, and solid-state electrolytes. Its exceptional thermal stability, chemical inertness, and 2D structure enable significant enhancements in ionic conductivity, thermal management, and interfacial stability. By mitigating challenges such as dendrite formation, side reactions, and poor mechanical integrity, h-BN holds great promise over critical bottlenecks in current battery technologies.

The integration of h-BN into electrolyte systems is still in its early stages, but its potential to revolutionize energy storage technologies is undeniable. Overcoming the current challenges and leveraging emerging opportunities could enable h-BN to play a pivotal role in developing safer, more efficient, and more durable LIBs. Exploring hybrid architectures that combine h-BN with other nanomaterials could lead to multifunctional electrolytes with enhanced properties. Such nanocomposites could offer synergistic effects, improving ionic conductivity, thermal management, and mechanical stability. Besides, developing advanced in-operando characterization techniques will be crucial for understanding the interactions between h-BN and electrolyte matrices at the molecular level. Such insights could guide the rational design of next-generation h-BN-enhanced electrolytes. Focusing on the environmental impact and recyclability of h-BN materials is also critical for sustainable energy storage solutions. Exploring greener synthesis routes and developing recycling protocols for h-BN-enhanced electrolytes will align with the global push toward sustainability.

In conclusion, h-BN offers unique opportunities to advance the performance, safety, and durability of next-generation battery systems. Despite all the advances, challenges such as achieving uniform dispersion, optimizing functionalization, and addressing cost constraints remain. Exploring h-BN's potential in emerging battery chemistries, stimuli-responsive electrolytes, and sustainable applications could unlock new frontiers in energy storage.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Gulsah Yaman Uzunoglu: conceptualization (equal); funding acquisition (lead); investigation (equal); project administration (lead); writing—original draft (equal); writing—review and editing (equal). **Sahin Coskun**: conceptualization (supporting); investigation (supporting); writing—original draft (supporting); writing—review and editing (supporting). **Recep Yuksel**: conceptualization (equal); investigation (equal); supervision (lead); writing—original draft (equal); writing—review and editing (equal).

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