

Research Progress of Polyimide-based Lithium-ion Batteries

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Abstract

Lithium-ion batteries (LIBs), as core energy storage devices in the new energy sector, are increasingly employed in electric vehicles, smart grids, and other applications, driving rising demands for higher energy density, longer cycle life, and enhanced safety. Polyimide (PI), with its outstanding thermal stability, mechanical strength, and chemical inertness, offers unique advantages for optimizing the performance of key LIBs components. This review systematically summarizes recent advances in PI-based materials for LIBs separators, binders, and electrode materials, emphasizing structural design, fabrication strategies, performance enhancement, and application outcomes. Furthermore, current challenges in the development of PI-based LIBs are discussed, and future research directions are proposed, providing a reference for the design and engineering of high-performance lithium-ion batteries.

Keywords

Polyimide, Lithium-ion battery, Separator, Binder, Electrode material, Performance optimization

Introduction

As the global energy system shifts toward cleaner, low-carbon sources, the large-scale deployment of renewable energy, including wind and solar power, necessitates advanced energy storage technologies [1]. Lithium-ion batteries (LIBs) have emerged as the dominant energy storage technology for electric vehicles, portable electronics, and grid-scale systems due to their high energy density, long cycle life, and relatively low environmental impact [2]. Nevertheless, conventional LIBs encounter critical challenges, including thermal runaway and limited cycling stability, especially under high-energy-density conditions. The performance of key components including separators, binders, and electrode materials directly governs the overall efficiency and safety of the battery [3].

Separators function as physical barriers that isolate the cathode and anode while facilitating lithium-ion transport. Commercial separators are primarily composed of polyolefins, including polyethylene (PE) and polypropylene (PP), which exhibit limited thermal stability (melting points of approximately 130 °C for PE and 160 °C for PP). At elevated temperatures, these materials may melt and shrink, potentially leading to

internal short circuits and triggering thermal runaway [4]. Binders ensure robust adhesion among the active material, conductive additives, and current collectors within the electrode structure. However, conventional polyvinylidene fluoride (PVDF) binders exhibit limited thermal stability and weak interfacial adhesion, potentially leading to structural degradation under high-voltage and prolonged cycling conditions [5].

Electrode materials, which fundamentally dictate energy storage capacity, are constrained by intrinsic capacity limitations and pronounced volume expansion in conventional inorganic systems. Therefore, the development of electrode materials with high capacity and structural stability is essential for improving battery energy density [6].

Polyimide (PI) is a high-performance polymer characterized by its imide ring structures. It exhibits outstanding thermal stability (decomposition temperatures typically above 500 °C), high mechanical strength (tensile strengths of 10-200 MPa), chemical resistance, and favorable electrolyte affinity [7]. Furthermore, its molecular structure offers exceptional tunability. Through monomer selection, functional group

incorporation, and composite engineering, the pore structure, interfacial properties, and electrochemical performance of PI-based materials can be precisely tailored to meet the requirements of various LIBs components [8].

In recent years, substantial progress has been made in applying PI-based materials to LIBs separators, binders, and electrodes, offering promising strategies to overcome the limitations of conventional materials. This review systematically summarizes recent advances in PI-based materials for key LIBs components, elucidates their structure property relationships, and discusses prevailing challenges and future research directions.

Research progress of polyimide-based lithium-ion battery separators

As a crucial component of lithium-ion batteries, the separator plays a pivotal role in ensuring battery safety, cycling stability, and rate performance. Owing to their excellent thermal stability and structural tunability, PI-based separators have garnered significant attention as next-generation alternatives to conventional polyolefin separators.

Classification and structural design of PI-based separators

Based on fabrication methods and structural features, PI-based separators can be broadly categorized into three types: pure PI fibrous separators, PI composite separators, and PI modified separators. Pure PI fibrous separators are typically fabricated via electrospinning, exhibiting high porosity (60-90%) and a three-dimensional network architecture. Nevertheless, nonuniform pore size distribution and limited mechanical strength restrict their practical applications [9]. PI composite separators improve thermal stability, mechanical strength, and electrolyte affinity by incorporating inorganic fillers or organic polymers [10]. PI-modified separators optimize interfacial properties and suppress lithium dendrite formation through surface functionalization and crosslinking strategies [11].

Structural design is central to enhancing the performance of PI-based separators. Key principles include: (1) Constructing uniformly sized small pores (0.1-1 μm) and highly interconnected networks by optimizing spinning parameters and incorporating pore-forming agents to balance ionic transport and mechanical strength. (2) Introducing polar functional groups (e.g., hydroxyl and

amino) or electrolyte-philic coatings to improve wettability (contact angle $\leq 30^\circ$) and enhance ionic conductivity [12]. (3) Forming thermal barriers through inorganic thermally conductive fillers or crosslinking modifications to prevent significant thermal shrinkage at elevated temperatures ($>200^\circ\text{C}$) [13].

Preparation methods

(1) Electrospinning

Electrospinning is the primary technique for fabricating PI-based fibrous membranes. A high-voltage electric field draws a polyamic acid (PAA) precursor solution into continuous fibers, which are subsequently converted into PI via thermal imidization [14]. This method provides a straightforward processing route, high porosity, and scalability for large-scale production. By tuning parameters such as spinning voltage (10-20 kV), solution concentration (5-20 wt%), and collector distance (10-20 cm), fiber diameter (100 nm-1 μm) and pore architecture can be precisely controlled. Xiao et al. fabricated PI fibrous membranes using Oxydianiline (ODA) and Pyromellitic dianhydride (PMDA) monomers via electrospinning followed by gradient thermal imidization [15]. The resulting membranes exhibited 86.2% porosity and 400% saturated electrolyte uptake, but the tensile strength was limited (4.2 MPa), necessitating further composite modification.

(2) Composite modification

Composite engineering represents an effective strategy to enhance the overall performance of PI-based membranes. In inorganic - organic systems, nanoparticles such as nano- Al_2O_3 and SiO_2 incorporated into the PI matrix improve thermal stability and mechanical strength, while simultaneously scavenging HF in the electrolyte and mitigating electrode corrosion [16].

Inorganic - organic composites combine complementary polymer properties by blending or laminating PI with PVDF or Polyacrylonitrile (PAN). For example, the tensile strength of a PI/PVDF - Hexafluoropropylene (HFP)/PI sandwich membrane increased from 3.48 MPa to 19.09 MPa after hot pressing, with porosity reaching 71.57% [17].

(3) Surface modification and crosslinking

Surface modification improves electrolyte wettability and interfacial compatibility by depositing functional layers, such as polydopamine (PDA) and Polymethyl methacrylate (PMMA), onto the PI membrane [18].

Crosslinking strategies form three-dimensional network structures via thermal or chemical methods to suppress fiber slippage at elevated temperatures. Chen et al. proposed an electrospinning-assisted melt thermal crosslinking method to fabricate crosslinked PI (c-PI) membranes, which exhibited an average pore size of 0.78 μm , thermal weight loss of 7% at 500 $^{\circ}\text{C}$, and 80% capacity retention after 1,600 cycles [19].

Performance optimization and applications

Performance optimization of PI-based membranes primarily focuses on thermal stability, mechanical strength, electrolyte affinity, and electrochemical performance. Pure PI membranes decompose above 500 $^{\circ}\text{C}$, while composite PI membranes show negligible thermal shrinkage at 300 $^{\circ}\text{C}$, outperforming polyolefin membranes [20]. Incorporation of inorganic fillers or crosslinking enables tensile strengths of 5-60 MPa [21]. Modified membranes exhibit liquid absorption rates of 300-600% and near-zero contact angles [22]. Ionic conductivities range from 1-3 mS cm^{-1} , with interfacial impedance below 300 Ω [23].

Application studies confirm that PI-based membranes substantially improve battery safety and cycling stability. Batteries with 5% $\text{Al}_2\text{O}_3/\text{PI}$ / Boehmite (BM) membranes retained 97.7% capacity after 100 cycles at 0.2C and 74.9% after 5C discharge. Crosslinked PI membrane batteries maintained 80% capacity after 1,600 cycles at 10C.

Research progress of polyimide-based lithium-ion battery binders

Although binders account for only 3-10 wt% of the electrode, they are essential for maintaining structural integrity and interfacial stability. PI-based binders exhibit significant advantages in high-voltage, long-cycle lithium-ion batteries owing to their excellent thermal stability and strong interfacial adhesion.

Structural design principles

The core of PI-based binder design lies in balancing bond strength, thermal stability, and electrochemical compatibility. Key design principles include:

- (1) Incorporating polar groups such as hydroxyl (-OH), carboxyl (-COOH), and amino (-NH₂) into the polymer chain to form strong interactions with electrode surfaces via hydrogen and ionic bonding [24].
- (2) Combining rigid monomers (PMDA, ODA) with flexible segments (Polyethylene glycol, lignin) to

balance mechanical strength and elasticity, mitigating electrode volume expansion.

- (3) Constructing three-dimensional networks via thermal or chemical crosslinking to suppress electrolyte-induced swelling (swelling rate <30%).

Main preparation methods

- (1) Solution polycondensation method

In this method, PAA is synthesized via polycondensation of dianhydride and diamine monomers in polar solvents, followed by thermal imidization to yield PI. This mature approach allows precise control over molecular structure and molecular weight (10^4 - 10^5) by adjusting monomer ratios and reaction parameters (temperature 0-5 $^{\circ}\text{C}$, time 4-24h) [25].

- (2) Composite modification method

Composite modification involves combining PI with other polymers (PAA, PDA) or inorganic particles to synergistically enhance bonding performance and electrochemical stability. Tan et al. combined PI with adenine derivatives to fabricate a bifunctional adhesive exhibiting both high bond strength and flame retardancy [26]. While Kang et al. grafted borate ester and dopamine onto PAA to impart self-healing capability and mitigate silicon anode volume expansion [27]. Successful composite modification requires uniform dispersion and interfacial compatibility of all components, typically achieved via ultrasonic dispersion combined with mechanical stirring.

Performance optimization and applications

Performance optimization of PI-based binders primarily targets bond strength, thermal stability, electrolyte resistance, and electrochemical compatibility.

- (1) Bond strength: PI-based binders exhibit peel strengths of 0.3-0.5 N/mm, significantly higher than traditional PVDF (0.1-0.2 N/mm), effectively suppressing active material detachment [28].
- (2) Thermal stability: PI-based binders generally exhibit decomposition temperatures above 500 $^{\circ}\text{C}$, markedly surpassing PVDF (~400 $^{\circ}\text{C}$) and preventing bond failure at elevated temperatures.
- (3) Electrolyte resistance: Swelling rates remain below 30%, considerably lower than PVDF (>100%), ensuring electrode structural stability during extended cycling.
- (4) Electrochemical compatibility: Negligible decomposition occurs at voltages above 4.3 V, enabling use in high-energy-density batteries.

Application studies indicate that PI-based binders

substantially enhance electrode cycling stability and safety performance. Wang et al. fabricated hydroxyl/carboxyl-functionalized PI binders, achieving 73% capacity retention for $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ (NCM811) cathodes after 100 cycles at 4.7 V [29]. Qian et al. demonstrated that PI binders substantially enhance battery flame retardancy and mitigate the risk of thermal runaway [30].

Research progress of polyimide-based lithium-ion battery electrode materials

PI-based electrode materials have emerged as a research hotspot among novel organic electrodes owing to their high theoretical capacity, structural stability, and environmental friendliness. They can serve as active materials for either anodes or cathodes in lithium-ion batteries.

Structural design principles

The core of PI-based electrode material design lies in enhancing specific capacity, cycling stability, and electrical conductivity. Key design principles include:

- (1) Porous structure construction: Fabricating porous structures (pore size 10-100 nm) via templating and phase separation methods to increase specific surface area ($> 50 \text{ m}^2/\text{g}$) and provide abundant lithium-ion storage sites and transport pathways.
- (2) Conjugated structure introduction: Building conjugated aromatic ring networks via monomer selection to enhance electronic conductivity (10^{-4} - 10^{-2} S/cm).
- (3) Composite structure design: Integrating carbon materials (graphene, carbon nanotubes) or inorganic particles (Si, SnO_2) to synergistically enhance capacity and conductivity [31].

Main preparation methods

(1) Hydrothermal method

The hydrothermal method facilitates polymerization and self-assembly of PI monomers under high-temperature and high-pressure conditions to produce porous PI microspheres or nanostructures. This approach is straightforward, allowing precise control over morphology and structure by adjusting reaction temperature (150-250 °C), reaction time (2-6 h), and monomer ratio.

(2) Electrospinning method

Electrospinning enables fabrication of PI fibrous electrode materials with high porosity and three-

dimensional network structures, promoting lithium-ion transport and structural stability. Zhang et al. fabricated three-dimensional porous PI anode materials via electrospinning [32]. After 1,000 cycles at a high current density of 5 A/g, the capacity reached 907 mAh/g, three times higher than that of non-porous electrodes. Electrical conductivity can be further enhanced by incorporating conductive fillers such as Carbon nanotubes (CNTs) or graphene.

(3) Composite modification method

Composite modification involves integrating PI with high-capacity materials (Si, SnO_2) or conductive additives (graphene, carbon nanotubes) to synergistically enhance electrochemical performance [33]. Li et al. integrated PI with lithium N-(2-aminoethyl) glycine to fabricate layered PI cathode materials, achieving a discharge capacity of 138.3 mAh/g at 30 mA/g and 71% capacity retention after 5,000 cycles. PI/Si composite electrodes mitigate Si volume expansion ($>200\%$) via the PI matrix while leveraging Si's high capacity (4,200 mAh/g) to enhance battery energy density [34].

Performance optimization and applications

Performance optimization of PI-based electrode materials primarily targets specific capacity, cycling stability, and electrical conductivity.

- (1) Specific capacity: Porous PI microspheres exhibit theoretical capacities of 1000-1500 mAh/g, significantly exceeding that of conventional graphite electrodes (372 mAh/g).
- (2) Cycling stability: Structural design and composite modification enable PI-based electrode materials to achieve $>90\%$ capacity retention and $<20\%$ volume expansion after 100 cycles at 1 A/g.
- (3) Conductivity: Electronic conductivity can reach 10^{-2} - 1 S/cm after incorporating conductive additives, meeting requirements for high-rate charge-discharge applications. Application studies indicate that PI-based electrode materials substantially enhance battery energy density and cycling stability.

Challenges and prospects

Current challenges

Despite significant advantages in lithium-ion batteries, PI-based materials still face several challenges:

- (1) High cost: PI monomers (e.g., ODA and PMDA) are expensive, and their preparation processes (e.g., electrospinning and high temperature imidization) are

complex, leading to production costs 2-5 times higher than those of conventional materials.

(2) Limited processability: Pure PI exhibits poor solubility and high melting temperatures, hindering conventional processing methods such as injection molding and extrusion, thereby restricting large-scale production.

(3) Low intrinsic conductivity: Pure PI exhibits extremely low electronic conductivity (10^{-10} - 10^{-12} S/cm), requiring enhancement via conductive composites or structural modification, which increases process complexity.

(4) Interface compatibility: High interfacial impedance between certain PI-based materials and electrodes/electrolytes can impair battery rate performance.

(5) Trade-off in mechanical properties: Electrospun PI fiber separators often exhibit tensile strengths below 10 MPa, necessitating composite modification, which may compromise porosity and ion transport efficiency.

Future research directions

Future research on PI-based lithium-ion batteries should prioritize three major objectives: low cost, high performance, and scalable production. Key directions include:

(1) Low-cost synthesis: Developing renewable monomers (e.g., lignin and biomass derivatives) to replace conventional aromatic dianhydrides/diamines, and simplifying preparation processes (e.g., one-step imidization and atmospheric-pressure drying).

(2) Multifunctional integrated design: Creating PI-based composites with high conductivity, flame retardancy, and self-healing capabilities to simultaneously enhance battery performance and safety.

(3) Interface engineering: Employing molecular design to introduce functional groups or surface modifications that reduce interfacial impedance ($<100 \Omega$) and enhance interface stability.

(4) Novel structural design: Developing advanced PI-based architectures, including core-shell and gradient structures, to meet requirements of next-generation high-voltage (>4.5 V) and high-energy-density (>400 Wh/kg) batteries.

(5) Industrial-scale production: Optimizing process parameters to enable continuous fabrication of PI-based materials and reduce manufacturing costs [35].

Conclusion

In summary, polyimide-based materials, with their superior thermal stability, mechanical robustness, and structural tunability, have become pivotal candidates for addressing the bottlenecks of conventional lithium-ion battery components. These bottlenecks encompass issues related to safety, cycling stability, and high-voltage compatibility. Significant advancements have been achieved in the design and fabrication of polyimide separators, binders, and electrode materials, effectively elevating the overall performance of lithium-ion batteries. Nevertheless, challenges including high manufacturing costs, limited processability, and low intrinsic conductivity remain to be resolved. With continuous innovations in low-cost monomer development, multifunctional structural design, interface engineering, and scalable preparation technologies, polyimide-based materials are expected to break through application restrictions. They will provide robust material support for the development of next-generation high-safety, high-energy-density lithium-ion batteries.

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Authors' contributions

Penghao Yu and Jiaqi Xiao contribute equally to the article.

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Conflicts of Interest

The authors declare no conflict of interest.

References

- [1] Kabeyi, M. J. B., Olanrewaju, O. A. (2022) Sustainable energy transition for renewable and low carbon grid electricity generation and supply. *Frontiers in Energy Research*, 9, 743114.

- [2] Yoshino, A. (2019) Brief history and future of the lithium-ion battery. *The Nobel Prizes*, 207-218.
- [3] Massé, R. C., Liu, C., Li, Y., Mai, L., Cao, G. (2017) Energy storage through intercalation reactions: electrodes for rechargeable batteries. *National Science Review*, 4(1), 26-53.
- [4] Lingappan, N., Lee, W., Passerini, S., Pecht, M. (2023) A comprehensive review of separator membranes in lithium-ion batteries. *Renewable and Sustainable Energy Reviews*, 187, 113726.
- [5] Sudhakaran, S., Bijoy, T. K. (2023) A comprehensive review of current and emerging binder technologies for energy storage applications. *ACS Applied Energy Materials*, 6(23), 11773-11794.
- [6] Wang, Q., O'Carroll, T., Shi, F., Huang, Y., Chen, G., Yang, X., Zhang, D. (2024) Designing organic material electrodes for lithium-ion batteries: progress, challenges, and perspectives. *Electrochemical Energy Reviews*, 7(1), 15.
- [7] Yi, L., Huang, W., Yan, D. (2017) Polyimides with side groups: synthesis and effects of side groups on their properties. *Journal of Polymer Science Part A: Polymer Chemistry*, 55(4), 533-559.
- [8] Shi, Y., Zhou, X., Yu, G. (2017) Material and structural design of novel binder systems for high-energy, high-power lithium-ion batteries. *Accounts of Chemical Research*, 50(11), 2642-2652.
- [9] Yu, B., Chen, X., Jin, X., Zhang, X., Chen, L. (2024) Heat-resistant lithium-ion-battery separator using synchronous thermal stabilization/imidization. *ACS Applied Polymer Materials*, 6(5), 2464-2473.
- [10] Liu, W., Ju, J., Deng, N., Wang, L., Wang, G., Li, L., Cheng, B. (2020) Designing inorganic-organic nanofibrous composite membrane for advanced safe Li-ion capacitors. *Electrochimica Acta*, 337, 135821.
- [11] Song, X., Huang, W., Ge, R., Wang, H., Xing, J. (2024) Electrospun nanofibers constituted of a polyimide core decorated with polyhedral oligomeric silsesquioxanes and a tio₂ shell as separators for lithium-ion batteries. *ACS Applied Nano Materials*, 7(18), 21565-21577.
- [12] Yang, K., Liu, Z., Chai, J., Zheng, Y., Fu, X., huan Shen, Y., Shi, S. (2022) High performance polyimide-based separator for 4.5 V high voltage LiCoO₂ battery with superior safety. *Materials Chemistry and Physics*, 282, 125975.
- [13] Babiker, D. M., Wan, C., Mansoor, B., Usha, Z. R., Yu, R., Habumugisha, J. C., Li, L. (2021) Superior lithium battery separator with extraordinary electrochemical performance and thermal stability based on hybrid UHMWPE/SiO₂ nanocomposites via the scalable biaxial stretching process. *Composites Part B: Engineering*, 211, 108658.
- [14] Parsaei, S., Zebarjad, S. M., Moghim, M. H. (2022) Fabrication and post-processing of PI/PVDF-HFP/PI electrospun sandwich separators for lithium-ion batteries. *Polymer Engineering & Science*, 62(11), 3641-3651.
- [15] Xiao, M., Li, J., Lei, H., Zhang, M., Niu, H., Wu, D., Wang, X. (2020) Preparation and microstructure control of PMDA/ODA polyimide hollow fibers. *Fibers and Polymers*, 21(5), 944-953.
- [16] Ahn, J. H., You, T. S., Lee, S. M., Esken, D., Dehe, D., Huang, Y. C., Kim, D. W. (2020) Hybrid separator containing reactive, nanostructured alumina promoting in-situ gel electrolyte formation for lithium-ion batteries with good cycling stability and enhanced safety. *Journal of Power Sources*, 472, 228519.
- [17] Hu, H., Xue, W., Jiang, P., Li, Y. (2022) Polyimide-based materials for lithium-ion battery separator applications: a bibliometric study. *International Journal of Polymer Science*, (1), 6740710.
- [18] Khezraqa, H., Safavi-Mirmahalleh, S. A., Roghani-Mamaqani, H., Salami-Kalajahi, M. (2024) A review on polydopamine as an efficient material in different components of rechargeable ion batteries. *Journal of Energy Storage*, 79, 110170.
- [19] Chen, Y., Song, Z., Liu, H., Xu, H., Xi, Y., Yin, C., Zhou, L. (2024) Cross-linking synergistic effects to enhance the comprehensive properties of electrospun polyimide nanofiber membranes for advanced lithium-ion batteries. *ACS Sustainable Chemistry & Engineering*, 12(15), 5953-5964.
- [20] Huang, Z., Chen, J., Huo, Y., Zhao, J. (2021) Heat resistant microporous membranes based on soluble poly (aryl ether ketone) copolymers for lithium-ion battery separator. *Journal of Applied Polymer Science*, 138(35), 50895.
- [21] Sun, G., Liu, B., Niu, H., Hao, F., Chen, N., Zhang,

- M., Wu, D. (2020) In situ welding: superb strength, good wettability and fire resistance tri-layer separator with shutdown function for high-safety lithium-ion battery. *Journal of Membrane Science*, 595, 117509.
- [22] Guo, C., Luo, Z. H., Zhou, M. X., Wu, X., Shi, Y., An, Q., Zhou, G. (2023) Clay-originated two-dimensional holey silica separator for dendrite-free lithium metal anode. *Small*, 19(36), 2301428.
- [23] Heidari, A. A., Mahdavi, H. (2020) Recent development of polyolefin-based microporous separators for Li-ion batteries: a review. *The Chemical Record*, 20(6), 570-595.
- [24] Chen, Z., Li, S., Zhang, G., Yang, Y., Qian, Y. (2024) Renewable lignocellulose-based binders for advanced battery systems. *Green Chemistry*, 26(19), 9993-10005.
- [25] Xu, Y., Zhang, Q., Lv, N., Li, H., Wei, Z., Wang, Y., Tang, H. (2023) Carboxyl function group introduced to polyimide binders for silicon anode materials. *Energy & Fuels*, 37(3), 2441-2448.
- [26] Tan, W., Liang, B., Chen, M., Xiao, H., He, X., Yang, W., Yang, G. (2024) Rigid-flexible mediated co-polyimide enabling stable silicon anode in lithium-ion batteries. *Chemical Engineering Journal*, 496, 153822.
- [27] Kang, Y., Kim, S., Han, J., Yim, T., Kim, T. H. (2024) Poly (acrylic acid) grafted with a boronic ester and dopamine as a self-healable and highly adhesive aqueous binder for Si anodes. *ACS Applied Energy Materials*, 7(6), 2436-2450.
- [28] Zhao, Y., Liang, Z., Kang, Y., Zhou, Y., Li, Y., He, X., Li, B. (2021) Rational design of functional binder systems for high-energy lithium-based rechargeable batteries. *Energy Storage Materials*, 35, 353-377.
- [29] Wang, Y., Qi, K., Dong, N., Liu, B., Tian, G., Qi, S., Wu, D. (2022) Surface modification enabling 4.7 V nickel-rich layered cathode with superior long-term cyclability via novel functional polyimide binders. *Journal of Power Sources*, 545, 231927.
- [30] Qian, G., Wang, L., Shang, Y., He, X., Tang, S., Liu, M., Wang, J. (2016) Polyimide binder: a facile way to improve safety of lithium-ion batteries. *Electrochimica Acta*, 187, 113-118.
- [31] Das, P., Thompson, B. C. (2023) Development of design strategies for conjugated polymer binders in lithium-ion batteries. *Polymer Journal*, 55(4), 317-341.
- [32] Zhang, Q., Cheng, H., Wei, Z., Zhu, S., Yu, L., Jiang, Z., Tang, H. (2024) Three-dimensional porous polyimide anode for high-rate lithium-ion batteries. *Journal of Energy Storage*, 86, 111147.
- [33] He, X., Zhang, K., Zhu, Z., Tong, Z., Liang, X. (2024) 3D-hosted lithium metal anodes. *Chemical Society Reviews*, 53(1), 9-24.
- [34] Li, A., Xu, Y., Shi, J., Yuan, B., Cheng, F., Zhang, W. (2024) Lithium-copolymerized polyimide cathodes for stable and fast lithium-ion storage. *Chemical Engineering Journal*, 481, 148503.
- [35] Liu, S., Cheng, H. (2024) Manufacturing process optimization in the process industry. *International Journal of Information Technology and Web Engineering (IJITWE)*, 19(1), 1-20.