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The Polymer in Energy Storage: Enabling the Transition to a Sustainable Energy Future; Review

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Abstract

Polymer chemistry is a major game-changer for energy storage technologies and has a vital role in the energy transition to sustainable systems worldwide. This review identifies the major roles for polymers related to capacity enhancement, elemental safety, and ecological enhancement of batteries, supercapacitors, and other energy storage devices. Given their structural diversity, function variability, and cost effectiveness, polymers are an avenue for exploration of new materials such as polymer electrolytes, polymer electrolytes/additives, electrode binders, and conducting (e.g., functionalized) composites, while still addressing major concerns in lithium ion batteries (LIBs), sodium ion batteries (SIBs), or supercapacitors (e.g., energy density, cycle life, elemental safety, environmental impact). This review aims to highlight various applications, such as solid polymer electrolytes to enhance safety and prevent thermal runaway in LIBs; bio-derived binders for green development of electrodes in LIBs and SIBs; and conducting (e.g., functionalized) polymer composites, which enhance the specific capacitance of supercapacitors. This review also described challenges in energy storage utilizing polymers, including scaling up, cost, and problems associated with the raw materials in polymer synthesis and the final product itself, and suggested solutions (i.e., PFAS-free and recyclable) to prevent contamination of groundwater and waterways. Ethical issues, i.e., equitable access to advanced technologies (Li, Co, etc.), were also discussed over future directions, such as AI-assisted material discovery and biodegradable polymers for energy storage. This review highlights the prospects of exploiting polymer chemistry and sustainable practices to realize effective, green energy storage systems and the future of decarbonized energy.

Keyword: polymer chemistry, energy storage, sustainable energy, batteries, supercapacitors.

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Introduction

The transition from fossil fuels to renewable energy sources like solar and wind is a necessary move toward sustainable energy systems to mitigate climate change and aggressively reduce greenhouse gas emissions (1). Energy storage technologies [e.g., batteries and supercapacitors] are critical for addressing the intermittent nature of renewables and their capability to enlarge the possible applications, including, but not limited to, electric vehicles (EVs), grid storage, and portable electronics (2). Polymer chemistry is probably the next frontier in this evolution because of the various combinations of polymer properties such as structural flexibility, tunable conductivity, and environmental adaptability (3). Researchers are using different types of polymers for each of these energy storage components - an electrolyte, an electrode binder, a separator, or conductive additive; these polymers can also enhance various performance metrics, such as energy density, safety, and cycle life (4).

Solid polymer electrolytes (SPEs) in lithium-ion batteries (LIBs) provide a safer alternative to liquid electrolytes, due to a lower flammability risk. Similarly, bio-derived polymers could provide a sustainable alternative to traditional fluorinated polymers, such as polyvinylidene fluoride (PVDF), for potential use as binders (5). Conductive polymers (for example, polyaniline [PANI] or polypyrrole [PPy]) combined with other material components can improve charge storage capacity and coulombic efficiency in supercapacitor devices (6).

While there is increasing excitement about the potential of polymer-based materials for energy storage applications, several challenges remain, including production cost, scalability of practical use, and environmentally concerning sources relating to PFAS (per- and polyfluoroalkyl substances), as well as non-degradable polymers (7). In this review, we have synthesized the recent advances in polymer chemistry as it relates to energy storage, commented on significant barriers for implementation, and proposed pathways that promote sustainability in support of a decarbonized energy future.

Materials

This narrative review utilized databases such as PubMed, Scopus, Web of Science, and ScienceDirect, in order to synthesize the most recent (8) peer-reviewed studies (specifically designated to articles that were published but not past pre-print) during the time period.

frame of 2015 to 2025. Search terms used to screen the articles for inclusion were "polymer chemistry," "energy storage," "batteries," "supercapacitors," "sustainable energy," and "polymer electrolytes." Inclusion criteria examined whether the polymer study had examined polymer-based materials as it related to energy storage while emphasizing sustainability, performance, and technology as it relates to sustainability. Studies were eligible for inclusion if they examined lithium-ion batteries, sodium-ion batteries, supercapacitors, or emerging technologies in regard to polymer chemistry, as there is presently more traction in the field about batteries when developing polymer electronic materials, to curtail basis joint trends and produce valuable findings without limiting the breadth of direction (e.g., LiBs, SiBs).

Polymer Chemistry in Energy Storage

Polymer Electrolytes for Batteries:

Polymer electrolytes are now at the forefront of battery technology, providing a safer and more stable alternative to conventional liquid electrolytes. Solid polymer electrolytes (SPEs), particularly polyethylene oxide (PEO)-based systems, offer high ionic conductivity, mechanical strength, and address leakage and risks of thermal runaway in lithium-ion batteries (LIBs) (9). PEO-based electrolytes have ionic conductivities of ~10^{-3} S/cm at elevated temperatures when complexed with lithium salts such as lithium bis(trifluoromethanesulfonyl)imide (LiTFSI), but performance at room temperature remains approximately an order of magnitude lower (10). Advances have included the development of gel polymer electrolytes (GPEs) that capitalize on the flexibility of liquid electrolytes while offering the physical stability of solid electrolytes. (11) prepared a physically crosslinked GPE with carbon dots to form a three-dimensional interconnected structure, which provided a pathway for increased lithium-ion transport and stabilized the battery during cycling (11).

Polymer electrolytes are also important in the development of sodium-ion batteries (SIBs). Due to low abstraction costs and concerns regarding sustainable development, SIBs represent an attractive alternative to traditional LIBs due to the abundance of sodium (6). The flexible frameworks of redox-active polymers such as polyimides allow for fast sodium-ion kinetics, with reversible capacities ~150 mAh/g (12). Despite progress, challenges remain, including low ionic conductivity and poor interfacial compatibility with electrodes, thus requiring innovations such as the incorporation of ceramic filler (e.g., Al_2O_3) in composite electrolytes that would improve functionality (13).

Electrode Binders for Sustainable Electrodes

Electrode binders are critical to the performance of battery electrodes, as they maintain the structural integrity of the electrode and adhere the active materials to the current collectors. Traditional binders (e.g., PVDF, a polymer containing PFAS) are viable for this application; however, they are toxic persistent organic pollutants (POPs) (7). More sustainable alternatives, such as bio-derived polymers, such as carboxymethyl cellulose (CMC) and sodium alginate, are promising options due to their low-cost origin and biodegradable chemical structure (3).CMC has good adhesion and compatibility with aqueously processed electrodes, which can reduce dependence on highly toxic organic solvents for electrode preparation (5). Overall, the CMC-based binders have been shown to improve supercapacitor performance by increasing electrode stability, providing a capacitance retention of ~90% capacitance after 1000 cycles (14). In terms of sodium alginate, a reversible capacity of ~800 mAh/g was observed in Li-ion battery (LIB) anodes with silicon-based materials (16). Despite these advantages, bio-based binders tend to have lower mechanical strength than PVDF; thus, hybrid designs that combine both natural and synthetic polymers are necessary (16). Table 1 represents the polymer-based electrode binders in energy storage.

Table 1: Polymer-Based Electrode Binders in Energy Storage

Binder Material	Type	Applications	Advantages	Limitations	References
Polyvinylidene Fluoride (PVDF)	Synthetic (PFAS)	LIBs, Supercapacitors	High adhesion, chemical stability	Non-biodegradable, toxic	7
Carboxymethyl Cellulose (CMC)	Bio-derived	LIBs, SIBs, Supercapacitors	Biodegradable, low-cost, aqueous processing	Lower mechanical strength	3 17
Sodium Alginate	Bio-derived	LIB anodes, Supercapacitors	High capacity with Si anodes, eco-friendly	Limited scalability	15
Polyimides	Synthetic	SIBs, LIBs	High thermal stability, redox-active	Complex synthesis	12

Conductive Polymers for Supercapacitors

Conductive polymers like polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT) are effective for supercapacitors due to their high electrical conductivity and pseudocapacitive properties (6). For example, PANI can achieve specific capacitances of ~250 F/g in organic electrolytes, and graphene oxide (GO) composites can improve its cycling stability (18). PPy is also less conductive than PEDOT, but there is added flexibility with composite designs, as its particle size is larger than PEDOT, especially useful to account for reduced porosity (6). If added conductivity is needed, PEDOT is a great solution for high-rate supercapacitors, where it demonstrated ~85% capacitance retention after ~10,000 cycles (8).

Hybrid composite (e.g., PANI with reduced graphene oxide (rGO)) provides a combination of a conductive polymer with high capacitance, and a carbon-based material with mechanical stability (19). Both PANI and rGO hybrids helped solve their limitations, such as inconsistent cycling stability, thus making them suitable for specific applications in renewable energy storage systems, like wind farms (1). However, the synthetic expense is also a problem, as is the environmental impact of non-aqueous solvents used in processing (12). Table 2 provides an overview of the conductive polymers in supercapacitors.

Table 2: Conductive Polymers in Supercapacitors

Polymer	Specific Capacitance (F/g)	Applications	Advantages	Limitations	References
Polyaniline (PANI)	~250	Supercapacitors, Hybrid capacitors	High capacitance, low cost	Poor cycling stability	6 18
Polypyrrole (PPy)	~200	Supercapacitors	Flexible, easy to synthesize	Lower conductivity, porosity issues	6
PEDOT	~150	High-rate supercapacitors	High conductivity, stable	High cost	8
PANI/rGO Composite	~250	Supercapacitors	Enhanced stability, high capacitance	Complex fabrication	19

Polymer-Based Separators and Coatings

Polymer-based separators and coatings also contribute to the safety and overall performance of batteries by preventing short circuits and improving the stability of electrodes. Microporous polyolefins, such as polyethylene (PE) and polypropylene (PP), are used as standard separators in LIBs, due to their chemical stability, low cost, and simplicity to manufacture (21). However, their unrealized risk is their low thermal stability. The expanding shrinkage at elevated temperature can cause thermal runaway (9). Advancements in separator technology (i.e., polyimide-based membranes) are performing specifically well in terms of not just resembling these microporous polyolefins but also boasting better thermal stability (extending to 300°C in some materials) and stability under mechanical stress to further improve safety at higher energy densities (10).

Polymeric coatings, such as PVDF or PEO, as a coating on electrode surfaces, can provide improved interfacial stability and reduce dendrite formation in lithium metal batteries (8). The addition of PEO coating on lithium anodes was able to reduce side reactions with the electrolyte, extending the cycle life by ~20% in subsequent testing (13). Similar to polymer separator technology, a central problem with industry scalability for advanced polymer separators or coatings relates to the high cost associated with producing the coating, and in some instances, the complexity associated with the production process to manufacture the coating at a high rate (16).

Issues with Polymer-Based Energy Storage

Scalability and expense

Scaling polymer-based materials to commercial levels remains a major issue. Conductive polymers like PEDOT require expensive precursors and complicated synthesis approaches, leading to limitations in scaling up their use into large systems (20). Additionally, the bio-derived binder CMC is generally cheap, but achieving consistent qualities for industrial production is difficult (22). The expense of genetic sequencing for polymer design functionality parallels issues in pharmacogenomics, highlighting scalability and finding cheap synthesis methods (23).

2. Environmental impact

The environmental footprint incurred by the production of polymers is a concern, with toxic polyfluoroalkyl substance materials like PVDF resulting in long-term pollution and toxicity (7). Recycling lithium-ion batteries containing PFAS is challenging; the fluorinated by-products generated from PFAS may be released into the environment (12). Bio-derived polymers have a more sustainable profile than traditional approaches, but their degradation products need to be investigated for environmental shortcomings (9). Additionally, polymer synthesis is a high-energy process resulting in emissions; thus, greener methods of production are required (1).

Performance Restrictions

In spite of the improvement of energy storage capability by polymers, areas of improvement remain, like low ionic conductivity of SPEs and weak mechanical strength of bio-based binders (10; Table 3). The electrolytes of PEO-based systems have conductivities of ~10^{-6} S/cm at room temperature and cannot be applied for high-rate applications (9). Conductor polymers like PPy also exhibit low capacitance after prolonged cycles due to the loss of microstructure of the polymers (6). These limitations make novel architectures like hybrid composites and nanostructured polymers required (19).

Table 3: Challenges and Solutions in Polymer-Based Energy Storage

Challenge	Description	Potential Solutions	References
Scalability	High synthesis costs and complex processes	Develop low-cost precursors, optimize manufacturing	20 3
Environmental Impact	PFAS persistence, energy-intensive synthesis	Use bio-derived polymers, improve recycling	7 15
Low Ionic Conductivity	Limited performance of SPEs at room temperature	Incorporate ceramic fillers, design hybrid electrolytes	9 13
Mechanical Stability	Weak binders and separators	Hybrid bio-synthetic designs, nanostructured polymers	3 24

Ethical and Sustainability Issues

Equal access to the next generation of polymer-based energy storage technologies presents the overriding ethical challenge. Price premiums and availability of raw materials of high-end PEDOT and separators have undeserved implications for developing regions, widening global energy inequities (22). Environmental impacts of polymers manufacturing and of polymers waste disposal challenge polymers' life cycle ethics (12). For instance, the biodegradability of bio-based polymers as required would entail extensive testing beyond preventing unintended environmental degradation (15). Polymers use informed consent, as in the genetic testing example of the use of clinical practice, would be required to uphold stakeholder trust (25).

Sustainability would be increased even more by the combination of the circular economy and polymer chemistry. Recycling of LIBs, for example, can be engineered for PFAS-free electrodes, thereby addressing the wastes and requirements of resource extraction (7). Moreover, the use of renewable feedstocks to polymers, e.g., lignin or starch, can be compatible with the United Nations' Seventh Sustainable Development Goal (Sustainable

Development Goal 7, Affordable and Clean Energy) (26)

Incorporation of Emerging Technologies

Polymer chemistry is being increasingly combined with next-generation technologies like artificial intelligence (AI) and nanotechnology to advance materials discovery and optimization. AI-enabled predictions for polymer properties directly impact the forwardly directed construction of high-performance electrolytes and binders (27). Nanotechnology represents a broad means to increase polymer performance through inducing nano-structuring to produce nanostructured composites (e.g., PANI/rGO) that improve charge transport and stability (8). In addition, systems that remotely monitor battery performance (inspired by telehealth) through the use of sensors with polymer bases to optimize grid storage were originally conceptualized, and some systems are currently being prototyped (28).

Future Directions

Future directions should focus on the development of scalable, sustainable polymer materials with improved performance properties. Building upon the development of biodegradable polymers (e.g., polylactic acid (PLA) derivatives could replace PFAS-based materials and reduce harm to the environment (29). There are numerous research opportunities using AI-driven material discovery in combination with high-throughput screening to develop novel electrolytes and binders (30). Studies are still needed to assess lifetime impacts for all polymer-based energy storage systems, but especially important for long-term sustainability (31). Sustainable polymer production, provision of subsidies, and establishing a policy platform to invest in green sources of polymer materials and organize recycling of polymers will advance a durable transition into a sustainable energy future (32).

Conclusion

Polymer chemistry is a catalyst for advancing the development of energy storage technologies. Polymer chemistry allows for safer, more effective, and sustainable battery and supercapacitor technologies. Whether it is developing solid polymer electrolytes, bio-derived binders, or conductive composites, polymers can address key leading challenges with energy density, safety, and environmental footprint. The energy storage community certainly faces many challenges: scalability, cost, and performance obstacles remain for polymer technologies. However, new developments are being made with PFAS-free materials and AI-aided design. The combination of polymer chemistry with sustainable practices in the

The energy storage sector can help provide the solutions required to support the global shift to a decarbonized world and address urgent needs for leading clean energy systems. Ongoing research, policy implementation, and cross-disciplinary collaboration will allow polymer technologies to become essential contributors to sustainable energy storage solutions.

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البوليمر في تخزين الطاقة: تمكين الانتقال إلى مستقبل طاقة مستدام

تُعدّ كيمياء البوليمرات نقلة نوعية في تقنيات تخزين الطاقة، ولها دور حيوي في التحول الطاقي نحو أنظمة مستدامة عالميًا. تُسلّط هذه المراجعة الضوء على الأدوار الرئيسية للبوليمرات في تعزيز السعة، والسلامة العنصرية، والتحسين البيئي للبطاريات والمكثفات الفائقة وغيرها من أجهزة تخزين الطاقة. ونظرًا لتنوعها البنيوي، وتعدد وظائفها، وفعاليتها من حيث التكلفة، تُشكّل البوليمرات مجالًا واعدًا لاستكشاف مواد جديدة، مثل إلكتروليتات البوليمر، وإلكتروليتات/إضافات البوليمر، ومواد ربط الأقطاب الكهربائية، والمركبات الموصلة (مثل المركبات الوظيفية)، مع مراعاة أهم التحديات في بطاريات أيونات الليثيوم، وبطاريات أيونات الصوديوم، والمكثفات الفائقة (مثل كثافة الطاقة، وعمر الدورة، والسلامة العنصرية، والأثر البيئي). تهدف هذه المراجعة إلى تسليط الضوء على تطبيقات متنوعة، مثل إلكتروليتات البوليمر الصلبة لتعزيز السلامة ومنع الهروب الحراري في بطاريات أيونات الليثيوم؛ والمواد الرابطة المشتقة حيويًا لتطوير أقطاب كهربائية صديقة للبيئة في بطاريات أيونات الليثيوم والصوديوم. وتشمل هذه المراجعة مركبات البوليمر الموصلة (مثل المركبات الوظيفية)، التي تُحسّن السعة النوعية للمكثفات الفائقة. كما تتناول التحديات التي تواجه تخزين الطاقة باستخدام البوليمرات، بما في ذلك التوسع في الإنتاج، والتكلفة، والمشاكل المرتبطة بالمواد الخام في تصنيع البوليمر والمنتج النهائي نفسه، وتقترح حلولًا) مثل المنتجات الخالية من مركباتPFAS والقابلة لإعادة التدوير (لمنع تلوث المياه الجوفية والمجاري المائية. وتناقش المراجعة أيضًا القضايا الأخلاقية، مثل ضمان الوصول العادل إلى التقنيات المتقدمة (الليثيوم، والكوبالت، وغيرها)، بالإضافة إلى التوجهات المستقبلية، مثل اكتشاف المواد بمساعدة الذكاء الاصطناعي، والبوليمرات القابلة للتحلل الحيوي لتخزين الطاقة. وتُبرز هذه المراجعة آفاق استغلال كيمياء البوليمرات والممارسات المستدامة لتحقيق أنظمة تخزين طاقة فعالة وصديقة للبيئة، ومستقبل الطاقة الخالية من الكربون

الكلمات المفتاحية: كيمياء البوليمرات، تخزين الطاقة، الطاقة المستدامة، البطاريات، المكثفات الفائقة