

A Review of the Applications of Nanocomposites in Batteries

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Abstract. With the large-scale development of renewable energy worldwide, the demand for high-efficiency energy storage technologies has become increasingly urgent. The limited energy density and cycle life of traditional electrode materials have hindered further breakthroughs in battery technology. Nanocomposites, with their unique size, interfacial effects, and structural design flexibility, have become a key focus of research in the battery field. This paper systematically reviews the research progress and underlying mechanisms of nanocomposites applied in lithium-ion batteries, supercapacitors, and emerging technologies such as sodium-ion batteries and solid-state batteries. Analysis indicates that nanocomposites—including carbon-based materials, metal oxide, and polymer materials—can significantly enhance electrode conductivity, accelerate ion diffusion, and improve structural stability through the synergistic optimization of structure and composition. Although challenges such as high cost, particle agglomeration, and difficulties in large-scale fabrication remain, nanocomposites demonstrate broad application prospects in the design of high-performance energy storage systems. This study elucidates the key optimization mechanisms, providing a theoretical framework and conceptual guidance for the future development of high-performance electrode materials.

Keywords: nanocomposites, carbon-based material, polymer material, application

1. Introduction

As the global economy and society continue to develop, energy demand is rising. Meanwhile, excessive consumption of fossil fuels has caused severe environmental problems and strained energy supply. Thus, the large-scale development and utilization of renewable energy sources such as solar and wind power have become the primary direction for the global energy transition. However, the intermittency and variability of these sources pose challenges, driving the need for efficient energy storage technologies.

In recent years, the global battery energy storage market has experienced rapid growth. According to the International Energy Agency (IEA), investment in the global battery energy storage sector surged to over \$65 billion in 2025, with new installed capacity for lithium-ion energy storage reaching 317 GWh—a year-over-year increase of approximately 74% [1]. At the same time, new energy storage systems such as sodium-ion and lithium-sulfur batteries, are emerging placing higher demands on the energy density and cycle life of electrode materials. In this context, the introduction of nanocomposites has offered new routes to overcome the performance bottlenecks of traditional

electrode materials. Farsi et al. pointed out in their review that nanocomposite-based electrodes can significantly enhance a battery's power density and fast-charging capability, offering distinct advantages over traditional electrodes [2].

As traditional electrode materials have limitations in energy density, cycle life, and rate capability, which hinder further breakthroughs in battery technology. Nanocomposites, with their unique size, interfacial effects, and structural design flexibility, offer a new direction for addressing these limitations and have become a research focus in the battery field.

This paper systematically reviews the research progress on nanocomposites applications in various battery and energy storage systems, summarizes their mechanisms and performance enhancements, and provides reference and guidance for research and engineering practice in related fields.

2. Energy storage technologies

2.1. Lithium-ion batteries

Lithium-ion batteries are the core devices in electrochemical energy storage; they operate via the reversible migration of lithium ions between the positive and negative electrodes. During charging, lithium ions are deintercalated from the cathode and migrate through the electrolyte to the anode, while electrons flow through the external circuit to the anode, maintaining charge balance; during discharge, lithium ions return from the anode to the cathode, and electrons release energy through the external load. This reversible ion migration occurs throughout the entire charge-discharge cycle and constitutes an electrochemical energy storage mechanism that converts chemical energy into electrical and vice versa [3].

Lithium-ion batteries consist of three core components: the cathode, the anode, and the electrolyte. The anode is typically made of carbon-based materials such as graphite or alloy and serves as the primary storage medium for lithium ions during charging; the cathode is primarily composed of transition metal oxides (such as LiCoO_2) or phosphates (such as LiFePO_4) and is responsible for the intercalation and deintercalation of lithium ions during charging and discharging; the electrolyte, which serves as the medium for lithium-ion migration, is an organic carbonate solution containing dissolved lithium salts. Research on solid-state batteries, however, focuses on replacing liquid electrolytes with solid-state electrolytes to overcome the performance and safety limitations of existing batteries [4].

2.2. Supercapacitors and other energy storage systems

The energy storage mechanisms of various technologies differ markedly: batteries rely on electrochemical reactions to store energy, based on the processes of ion deintercalation and intercalation as well as electron transfer; therefore, they possess a high energy density, meaning they can store more energy per unit mass or volume. Supercapacitors, in contrast, store energy via surface charge storage, including double-layer capacitance (where ions adsorb onto the electrode surface to form a charge layer) and pseudocapacitance (rapid redox reactions at the electrode surface). This energy storage method gives them a distinct advantage in power density—they can respond rapidly to energy demands and achieve high-rate discharge, making them indispensable in scenarios requiring instantaneous power supply [3].

As a key alternative to lithium-ion batteries, sodium-ion batteries share similar operating principles and structure, but offer three notable advantages. First, sodium is abundant, far exceeding

lithium reserves, alleviating resource scarcity issues; second, raw material costs are lower, significantly reducing cost barriers to large-scale production; third, sodium and lithium are both alkali metals with similar electrochemical properties, enabling compatibility with existing lithium-ion battery manufacturing processes and accelerating their commercialization [5].

Solid-state batteries are a key direction for the next-generation energy storage, with the core innovation being the replacement of traditional liquid electrolytes with solid-state electrolytes. This change fundamentally enhances safety: solid-state electrolytes eliminate the risks of leakage and flammability, thereby mitigating the risk of thermal runaway; second, energy density is significantly improved; solid-state electrolytes are compatible with high-capacity electrode materials, and the electrodes can be stacked more densely, reducing the proportion of inactive components; third, solid-state electrolytes possess superior thermal and chemical stability, broadening the battery's operating temperature range while also being compatible with high-voltage electrode systems, thereby opening up new possibilities for the development of high-performance energy storage devices [6]. There are performance and safety bottlenecks in batteries [4].

3. Nanocomposites for energy storage

3.1. Definition and properties of nanocomposites

Nanocomposites are materials composed of two or more components, at least one of which has characteristic dimensions in the nanoscale range of 1–100 nm. Common examples include carbon nanotube composites and graphene composites. These nanoscale properties offer numerous advantages for energy storage: First, the nanostructure provides an extremely large specific surface area, offering more active sites for electrochemical reactions and significantly improving reaction efficiency; second, the nanoscale conductive network enhances the material's electronic conductivity and reduces internal resistance; third, the nanostructure improves the material's mechanical stability, mitigating volume expansion issues during charging and discharging; fourth, the nanoscale shortens ion diffusion paths, enabling faster ion transport and thereby enhancing charging efficiency. These characteristics collectively make nanocomposites promising energy storage materials [7].

3.2. Carbon-based and metal oxide nanocomposites

The core advantage of carbon-based nanocomposites is their excellent electrical conductivity, which forms a continuous conductive network within the composite, significantly improving electron transport efficiency and overall battery performance [8]. Such materials have been widely applied in energy storage devices such as lithium-ion batteries and supercapacitors, and are a major research focus in the field.

Metal oxide nanocomposites (such as MnO_2 , TiO_2 , and Fe_3O_4) exhibit high energy storage capacity, good electrochemical activity, and structural stability, making them very essential. However, most metal oxides have poor intrinsic conductivity, limiting their direct application. Therefore, they are often combined with carbon materials to compensate for this shortcoming through the high conductivity of carbon, while leveraging the high capacity of metal oxides for complementary performance [9].

3.3. Polymer nanocomposites and current challenges

Polymer nanocomposites are of two types: conductive polymers and polymer electrolytes. Their prominent features include good flexibility and light weight, making them well-suited for the needs of flexible electronic devices and wearable energy storage devices, and providing important support for the development of flexible energy storage technology [10].

Although nanocomposites have demonstrated tremendous potential in energy storage, their practical application still faces numerous challenges: First, the high cost of preparing nanomaterials limits large-scale industrial application; second, nanoparticles are prone to agglomeration, causing performance degradation; third, achieving large-scale, reproducible preparation of nanocomposites remains a pressing challenge. These issues hinder the adoption of nanocomposites in energy storage systems; further research is needed to advance their transition from the laboratory to practical applications.

4. Applications of nanocomposites in energy storage devices

4.1. Applications in lithium-ion batteries

Lithium-ion batteries are the core power technology for electric vehicles, consumer electronics, and grid energy storage. However, traditional electrode materials generally suffer from poor electronic conductivity, slow ionic diffusion, and structural degradation during cycling, which limit improvements in battery energy density and cycle life. Owing to synergistic effects on their structure and composition, nanocomposites optimize electron transport and ionic diffusion kinetics, providing an effective path to overcoming these bottlenecks.

Carbon-based nanomaterials such as graphene and carbon nanotubes (CNTs) can form continuous three-dimensional conductive networks, significantly enhancing the overall conductivity of the electrode; metal oxides, in contrast, offer high theoretical specific capacity. When these two materials are combined, the resulting composite possesses both excellent electron transport capabilities and high energy storage capacity, effectively improving the battery's energy density, cycling stability, and charge-discharge efficiency. This is an important direction for developing high-performance lithium-ion battery electrode materials.

4.2. Applications in supercapacitors

Supercapacitors, known for rapid charging and discharging and high power density, are widely applied in requiring short-term, high-power output. However, their low energy density limits their wider applications; therefore, the improvement of electrode materials which combine high specific capacity with excellent conductivity is critical.

Graphene and carbon nanotubes possess high specific surface areas and excellent intrinsic conductivity, providing many active sites for charge storage. Hybrid nanocomposites such as graphene/manganese dioxide can combine the high conductivity of carbon materials with the pseudocapacitive properties of metal oxides, enhancing electrochemical performance. This improves the electrode's specific capacitance, charge transfer efficiency, and cycle life, meeting the needs of high-power energy storage applications.

4.3. Applications in emerging technologies

Polymer-based nanocomposites combine flexibility, light weight, and good mechanical stability, making them well-suited for flexible electronic devices. They are used in wearable electronics, flexible batteries, and flexible supercapacitors, providing a material foundation for portable and wearable energy storage devices.

In new energy vehicles and renewable energy storage, nanocomposites can significantly enhance the charging and discharging efficiency, cycling stability, and energy storage capacity of electrodes, thereby helping to improve the performance of power batteries and grid energy storage systems. They demonstrate significant application potential in electric vehicles and renewable energy grid-connected storage scenarios.

5. Conclusion

This paper reviews nanocomposite applications in energy storage devices, systematically summarizing recent research and application progress in lithium-ion batteries, supercapacitors, and emerging energy storage technologies. The analysis indicates that through the synergistic optimization of structure and composition, nanocomposites offer significant advantages in enhancing electrode conductivity, ionic diffusion capacity, and structural stability, demonstrating broad application prospects in the field of energy storage.

This study's theoretical contribution is clarifying the key optimization mechanisms for nanocomposites in energy storage, by reviewing and synthesizing existing findings, which offers a reference for future related research. Practically, the analysis in this paper offers insights for the design and development of high-performance energy storage electrode materials. However, as this study is a literature review, it does not include original experimental data and lacks direct verification of performance in real-world application scenarios. Future research will explore the application of nanocomposites in actual energy storage systems, combining experimental validation with case studies to further advance the practical implementation of related technologies.

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