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Recent Advances of Nanocomposite Electrode Materials for Lithium-Ion and Sodium-Ion Batteries

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Abstract. Lithium-ion batteries (LIBs) and sodium-ion batteries (SIBs) are the two most significant battery technologies for electric vehicles (EVs) and large-scale energy storage systems; however, conventional single-electrode materials exhibit large volume changes, limited electronic conductivity, and sluggish ion diffusion kinetics that compromise their cycle life and rate capability. A literature review approach is used in this study to synthesize the existing findings regarding nanocomposite electrode materials for LIBs and SIBs. It has been found that heterostructure, core-shell, and three-dimensional network nanocomposites can be effectively synthesized to mitigate pulverization and enhance charge transport kinetics. Additionally, high production costs, low tap density, and ill-defined degradation mechanisms during long-term cycling pose significant challenges to the industrialization of nanocomposite electrodes. Finally, promising research directions include waste-derived green nanocomposites, AI-assisted material design, and continuous manufacturing for industrial-scale synthesis, which may provide systematic guidance for the further development of battery electrode materials.

Keywords: Nanocomposite electrodes, Lithium-ion batteries, Sodium-ion batteries, Energy storage, Electrochemical performance

1. Introduction

Driven by the accelerated global push for carbon neutrality, the large-scale integration of wind and solar power necessitates high-capacity energy storage systems, and electric vehicles (EVs) demand stringent performance criteria for energy density, cycle life, and safety of secondary (rechargeable) batteries. Over the past 30 years, lithium-ion battery (LIB) technology has dominated consumer electronics and the EV sector; however, lithium reserves are limited, and rising raw material costs hinder their large-scale deployment [1]. Sodium-ion battery (SIB) technology, which shares similar electrochemical principles with LIBs, has emerged as a promising alternative energy storage technology [2]. Traditional electrode materials exhibit inherent limitations when used as standalone materials. Alloy anodes experience volume expansion exceeding 300% during lithium/sodium ion intercalation and deintercalation, leading to anode pulverization and substantial capacity degradation; pristine inorganic cathode materials exhibit low intrinsic electronic conductivity and sluggish Na^+/Li^+ transport kinetics [3]. Most earlier reviews focused solely on anode/cathode materials for LIBs only. Zhang et al. demonstrated that the microstructures of carbon-based

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nanocomposites can be regulated; however, the operating mechanisms underlying the divergent lithium and sodium storage behaviors remain insufficiently clarified [4]. Rayhan et al. have demonstrated that material costs could be minimized by employing nanocarbon carriers derived from waste biomass, although this approach remains underutilized in battery electrode manufacturing [5].

This study employs a systematic literature review methodology. Peer-reviewed articles on LIB/SIB nanocomposite electrodes published between 2018 and 2025 are synthesized, composite structures are systematically classified, the electrochemical performance of various electrode systems is compared, and current technical challenges and future research prospects are identified.

Theoretically, this review elucidates the synergistic charge storage mechanisms of multi-phase nanocomposites in lithium and sodium storage. Practically, the identified strategies of structural optimization and green synthesis provide practical guidelines for engineers developing low-cost, high-performance electrode materials and may facilitate the industrialization of low-cost sodium-ion energy storage systems [4].

2. Classification of nanocomposite electrode materials for LIBs/SIBs

2.1. Classification based on continuous matrix materials

2.1.1. Carbon-based matrix nanocomposites

Graphene, carbon nanotubes, MXene, and hard carbon are the most popular matrices for battery electrodes due to their high electrical conductivity, uniform layered structure, and diverse pore structures [4]. The carbon matrix can either encompass or anchor inorganic active material nanoparticles, thereby ensuring the continuity of conductive networks and reducing volume strain during cycling. Typical examples include SnO_2/graphene, FeS_2/carbon nanotubes, and MXene/Prussian blue composite electrodes. Green matrices derived from agricultural and fishery wastes are cost-effective and can significantly reduce raw material costs in electrode manufacturing [5]. Such nanocomposites have been applied as both cathodes and anodes, accounting for over 70% of laboratory research on electrode nanocomposites [3].

2.1.2. Inorganic compound matrix nanocomposites

The matrix comprises metal oxides, sulfides, phosphates, and Prussian blue analogs, and serves as a reinforcing filler along with nanocarbon or metal particles. The matrix can accommodate lithium/sodium ions, while nanofillers can enhance both electronic conductivity and mechanical strength. Representative systems include $LiFePO_4$/carbon black and $Na_2Ti_3O_7$/MXene nanocomposite anodes and cathodes. Nonetheless, the matrix materials are inorganic, and excessive incorporation of nanofillers compromises the tap density of the electrodes, thereby reducing the volumetric energy density of full cells [6].

2.2. Classification based on the dimensionality of nanoscale reinforcing fillers

2.2.1. Zero-dimensional (0D) nanoparticle composite electrodes

The 0D fillers consist of metals, metal oxide quantum dots, and nanocrystals with characteristic dimensions below 100 nm, which are uniformly dispersed in carbon-based or inorganic matrices. The extremely small particle size reduces Li^+/Na^+ diffusion distances, but these particles exhibit high

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surface energy and tend to agglomerate during the slurry coating process, resulting in uneven electrochemical reactions [4]. A representative SIB anode material is the Sn quantum dot/hard carbon composite.

2.2.2. One-dimensional (1D) and two-dimensional (2D) nanowire/nanorod composite electrodes

Carbon nanotubes and metal sulfide nanorods serve as conductive scaffolds, and active nanoparticles are synthesized in situ on their surfaces, forming interpenetrating networks. Their high aspect ratio facilitates long-distance electron transfer, preventing particle detachment during extended cycling [7]. Silicon nanowire/carbon composite anodes have been extensively investigated as high-capacity electrode materials.

Graphene, MXene, and layered double hydroxide (LDH) nanosheets are well-known 2D fillers that form heterointerfaces with active materials and induce built-in electric fields, thereby accelerating charge carrier separation kinetics. The layered structure can accommodate volume expansion of active materials, resulting in remarkable rate capability [8]. Flexible MXene composite electrodes are currently actively investigated for flexible LIB/SIB applications.

2.3. Classification based on micro composite structure

2.3.1. Core-shell structured nanocomposite electrodes

The core comprises active material nanoparticles, while the protective shell consists of conductive carbon or inert oxides. The shell serves as a protective barrier that prevents direct contact between active materials and the electrolyte, thereby mitigating electrolyte decomposition, inhibiting particle aggregation, and maintaining particle integrity during repeated ion intercalation and deintercalation [6]. The TiO_2@carbon core-shell anode has demonstrated stable cycling over 1000 cycles in SIB half-cells.

2.3.2. Heterojunction nanocomposite electrodes

The integration of two distinct semiconductor nanomaterials generates substantial internal electric fields, thereby enhancing ion migration kinetics. An effective strategy to overcome the poor conductivity of metal chalcogenide electrodes is to employ heterostructural design [7].

2.3.3. Three-dimensional (3D) self-supporting network composite electrodes

The nanofillers interact to form porous self-supporting networks without additional binders, while interconnecting pore channels accelerate electrolyte infiltration and ion transport. Such electrodes have been employed in flexible and foldable micro-batteries, but their application remains limited due to low packing density, restricting their suitability to large-scale energy storage systems [4].

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3. Application progress of nanocomposite electrodes in LIBs and SIBs

3.1. Nanocomposite anode materials

3.1.1. Alloy-type nanocomposite anodes

Alloy-type anode materials based on tin, silicon, and bismuth deliver exceptionally high theoretical specific capacities, yet severe volume variation during cycling frequently leads to electrode failure. Incorporating a carbon matrix or two-dimensional MXene sheets can effectively alleviate such structural degradation. For instance, the Sn/MXene composite anode delivers a reversible capacity of 682 mAh g^{-1} at 0.2 A g^{-1}, retaining 82 % of its initial capacity after 500 cycles [6]. Waste fish-bone-derived porous carbon can serve as a carrier for tin nanoparticles. Compared with a pure graphene matrix, this strategy reduces electrode material cost by up to 40% [5].

3.1.2. Transition metal compound composite anodes

Transition-metal oxides, sulfides and selenides possess abundant redox sites for lithium- and sodium-ion storage, while their poor intrinsic electronic conductivity limits high-rate performance. Constructing heterostructure nanocomposites with carbon materials is an effective approach to enhance electrochemical reaction kinetics. As a typical example, the $FeSe_2$/carbon nanotube composite anode delivers 456 mAh g^{-1} at 1 A g^{-1} for SIBs, with 76 % capacity retention over 800 cycles [7].

3.1.3. Carbon-based composite anodes

Hard carbon, soft carbon, and graphite composites represent the most commercially mature anode materials. N-doped carbon quantum dots/hard carbon nanocomposites provide abundant accessible active adsorption sites, which greatly improve the low-temperature discharge performance of sodium-ion batteries.

3.2. Nanocomposite cathode materials

Prussian blue analog (PBA) nanocomposites are promising cathode materials for SIBs. The open tunnel structure facilitates ion transport, whereas structural collapse originating from sodium-ion extraction and crystalline water dissolution remains a major challenge. Carbon nanocoating or MXene nanosheet modification can stabilize crystalline frameworks. The Fe-Fe PBA@carbon nanocomposite cathode demonstrates 91% capacity retention after 1000 cycles at 1 C.

Layered oxide nanocomposites are another important class of cathode materials. Layered lithium-transition-metal oxides (NCM, LCO) for LIBs and layered sodium oxides for SIBs can be modified with carbon nanotubes. Such modification improves surface electronic conductivity and suppresses undesirable interfacial side reactions between electrodes and electrolytes [3].

Polyanionic compound composite cathodes feature outstanding long-cycle stability. Typical representatives, such as $LiFePO_4$ and $Na_3V_2(PO_4)_3$, suffer from low intrinsic electronic conductivity, which hinders high-rate discharge capability. Nanocarbon coating composite strategies can overcome this drawback. Commercially available $LiFePO_4$/C nanocomposite cathodes have been widely adopted in power-type lithium-ion batteries [4].

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3.3. Application in flexible and full-scale energy storage batteries

Self-supporting 3D MXene/carbon composites are promising for flexible soft-pack LIB/SIB cells. These electrodes maintain structural integrity following 1000 folding cycles without mechanical disintegration [8]. For large-scale stationary sodium-ion battery energy storage systems, carbon-based nanocomposite electrodes can lower raw-material costs and satisfy the low-cost requirements of grid-scale energy storage systems [5].

4. Challenges and future directions of nanocomposite electrodes

4.1. Existing core challenges

4.1.1. Preparation and industrialization obstacles

The manufacturing cost of high-purity graphene and MXene nanofillers is relatively high; the majority of composite synthesis processes (solvothermal, electrostatic self-assembly) are bench-scale, and lack scalability. Slurry mixing and coating cannot effectively disperse nanoparticles, resulting in inconsistent electrochemical performance across batches [4]. Moreover, standardized technical parameters for the pretreatment of waste biomass for use as green carbon carriers are lacking [5].

4.1.2. Electrochemical performance defects

The poor tap density of nanocomposite electrodes compromises the volumetric energy density of full cells, despite their high gravimetric specific capacities. Capacity fade at low rates necessitates prolonged cycling, which promotes nano-active material agglomeration, heterointerface deterioration, and prolonged side reactions between high-specific-surface-area electrodes and the electrolyte [6]. A critical issue for SIB nanocomposite electrodes is that sodium ions are larger than lithium ions, thereby increasing structural strain.

4.1.3. Evaluation standard and environmental hidden dangers

No unified international standard has been established to date for characterizing nanocomposite electrode tap density, ion diffusion coefficients, and cycle decay mechanisms, which precludes comparison of experimental results across different research groups. The majority of nanostructured metal sulfide/oxide materials are non-recyclable once batteries are disposed of, and released nanoparticles pose potential ecological toxicity risks [1].

4.2. Future research development directions

4.2.1. Green low-cost composite preparation technology

Fishery waste (fish bones and processing residues) and agricultural straw should be utilized as raw materials to produce nanocarbon matrices via low-temperature pyrolysis, serving as replacements for high-cost graphene and carbon nanotubes to reduce electrode costs [5]. The development of aqueous-phase in situ composite technology is recommended to minimize organic solvent pollution during synthesis.

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4.2.2. Precise interface and microstructure regulation

To achieve homogeneous core-shell or heterojunction interfaces, electrostatic self-assembly and atomic layer deposition are recommended; to enhance ion transport efficiency and long-cycle structural stability, defect engineering and element doping should be employed [7]. Microspherical nanocomposite particles with high tap density should be developed to balance gravimetric and volumetric energy densities.

4.2.3. Intelligent material design and scaled production

Machine learning and artificial intelligence should be employed to optimize the ratio of active materials, nanofillers, and binders, thereby reducing material screening time [4]. Roll-to-roll continuous coating and calcination production lines should be established to facilitate industrial-scale production of nanocomposite electrodes.

4.2.4. Complete recycling and unified test standards

Low-temperature pyrolysis and solvent separation and recovery protocols for waste nanocomposite electrodes should be developed to enable the reuse of carbon carriers and active metals in subsequent cycles. A unified set of characterization and cycling test procedures for LIB/SIB nanocomposite electrodes should be developed, and the evaluation conditions for electrochemical performance should be standardized [1].

5. Conclusion

This study critically evaluates classification systems, lithium-/sodium-storage functions, and inherent limitations of nanocomposite electrodes via a systematic literature review of publications from 2018 to 2025. Consistent with the hypothesis that multiphase composite modification enhances LIB/SIB electrochemical performance, carbon-based, heterojunction, and core-shell nanocomposites effectively mitigate volume expansion and the poor conductivity inherent to single-component electrodes.

This review supplements existing literature by comparing nanocomposite performance in lithium- and sodium-ion systems and surveying green synthesis routes using fishery waste-derived biomass, topics rarely covered in previous electrode reviews. It extends prior single-electrode-material reviews by analysing nanocomposite electrodes across both battery systems. From a practical perspective, this work supports the development of low-cost sodium-ion cells and biomass-derived sustainable electrodes, providing structural-optimization insights for battery researchers.

Nevertheless, this review is limited to laboratory-scale electrochemical results, lacking systematic techno-economic analysis of industrial battery manufacturing. The thermal and overcharge safety characteristics of nanocomposite electrodes are also not discussed. Future work should conduct life-cycle assessments of waste-derived electrodes, investigate the thermal safety of heterojunction systems, and implement pilot-scale tests to verify the economic viability of biomass-carbon composites. Overall, this work clarifies the design-performance relationships of LIB/SIB nanocomposite electrodes and highlights the necessity for industrial-scale green manufacturing in sodium-ion battery commercialization.

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