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The recent advancement of electrode materials for batteries: A mini review

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A B S T R A C T

Battery electrode materials have advanced significantly, enabling the advancement of efficient energy storage systems. Throughout this mini-review, we emphasize innovations in lithium-ion batteries, emerging technologies, and the latest developments in anode and cathode materials. Several breakthroughs have been achieved, including the creation of electrodes that offer high voltages and flexibility, the development of metal–organic frameworks and derivatives to enhance electrode performance, and advancements in silicon-based anodes that address capacity and cycle life issues. Furthermore, the review highlights the shift from traditional intercalation materials to conversion-type electrodes, which provide increased specific capacities but are more challenging to stabilize. Additionally, new materials have been integrated to improve energy density, safety, and charging speed of solid-state batteries. A range of strategies, including doping, coating, and the integration of nanomaterials, is being utilized to address issues like material scarcity, safety concerns, and environmental effects. This review provides an extensive summary of current materials, synthesis techniques, and electrochemical mechanisms, along with future directions for developing effective electrodes aimed at producing long-lasting, efficient batteries with high energy density for upcoming applications.

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1. Introduction

In recent years, the demand for high-energy, safer, and longer-lasting rechargeable batteries has increased significantly, fueled by portable electronics, electric vehicles, and renewable energy storage solutions [1, 2]. Electrode materials are essential to these developments, substantially influencing the batteries' electrochemical performance, stability, and overall efficiency [3]. Advancements in electrode materials address challenges such as capacity fade and mechanical deterioration while also reducing production costs, paving the way for the next generation of high-performance batteries [1, 4].

The current market is largely influenced by conventional batteries that utilize inorganic cathode materials, primarily lithium

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iron phosphate and lithium cobalt oxide [5]. While these materials are effective, they also present challenges such as limited capacity, high production costs, and concerns regarding the safety of toxic metals [4]. Consequently, researchers are exploring alternative materials, including polymeric electrodes, which offer advantages like enhanced capacity, structural adaptability, and eco-friendliness [6]. Additionally, metal-based electrodes, such as tin foams, have emerged, surpassing traditional graphite electrodes in mechanical strength and charge storage abilities. These advancements are part of a broader initiative to diversify electrode chemistries to overcome the limitations of existing materials [4].

In the development of electrodes, modifying surface properties and engineering structures have become essential strategies that transcend material composition [7]. For instance, creating model electrodes with controlled morphology facilitates a deeper understanding of lithium-ion storage, while surface coatings enhance battery lifespan and interface stability. Furthermore, innovative crystalline structures, such as those found in niobium pentoxide electrodes, show great potential for accelerating charging times and increasing storage capacity by promoting lithium-ion transport and reducing degradation issues like lithium plating. These approaches underscore the importance of integrating electrochemical engineering with materials science to optimize electrode performance [8].

Despite these advancements, challenges persist in attaining optimal electrode performance, such as difficulties with material production, scalability, and safety [1]. Thorough evaluations highlight the necessity of tackling these issues through methods like doping, coatings, nanostructuring, and interface engineering to improve energy storage efficiency and extend battery lifespan [4, 9]. Additionally, developing durable, high-energy rechargeable batteries depends on the incorporation of effective electrolytes and the establishment of safety protocols [1, 10].

This article presents a comprehensive review of recent advancements in battery electrode materials, focusing on improvements in both cathode and anode performance. By analyzing progress and ongoing challenges, it seeks to provide insights into future research directions for electrode materials that will meet the changing needs of energy storage technologies across a range of applications, including consumer electronics, electric vehicles, and grid storage.

2. Types of electrode materials

Organic and inorganic electrode materials are essential in battery technology, each presenting unique benefits and challenges. Organic materials, made from carbon-based compounds, offer flexibility and sustainability, whereas inorganic materials, which are usually metal-based, provide high energy density and stability. Battery technology utilizes organic and inorganic electrode materials, each presenting advantages and disadvantages. Inorganic materials, typically composed of metals, provide stability and high energy density, while organic materials, consisting of carbon-based compounds, offer flexibility and sustainability.

2.1. Inorganic electrode materials

Inorganic materials offer numerous benefits over organic molecules, including larger surface areas, enhanced electrical conductivity, greater thermal stability, more active sites, and higher capacities, thereby broadening their potential for energy storage [11]. The development and efficiency of batteries, especially LIBs and emerging technologies like magnesium, aluminum, and sodium-ion batteries, depend significantly on inorganic electrode materials. These materials serve as cathodes or anodes, prized for their substantial theoretical capacities, ability to undergo multi-electron redox reactions, and structural stability. They typically include metal oxides, phosphates, or polyanion compounds [12]. For instance, inorganic cathode materials like lithium manganese oxide ($LiMn_2O_4$) and lithium iron phosphate ($LiFePO_4$) are widely used due to their environmental friendliness and relatively high discharge capabilities. However, they face challenges such as capacity fading caused by the dissolution of transition metals and high manufacturing costs related to complicated synthesis and limited raw materials [12].

Many inorganic nanomaterials, including metal oxides, metal phosphides, and oxysalt nanoparticles, have been extensively studied as LIB electrode materials [13, 14]. These nanoparticles' small size allows for a decrease in the diffusion channel between lithium ions and the collective electrode tension (mechanical stress/strain) brought on by Li insertion and removal [14]. However, their relatively low conductivity, especially in weak contact, is a serious problem [13, 15].

2.2. Organic electrode materials

Conducting polymers, radical, organosulfur, conjugated carbonyl compounds, and other redox-active organic materials with promising electrochemical characteristics were effectively introduced by the initial progress of organic electrodes [16]. Because they are made of lightweight, plentiful materials, batteries based on organic electrode materials have been regarded as a highly eco-friendly alternative to inorganic electrode materials. Additionally, their cost is lower than inorganic materials [17]. Fig. 1 displays the structure formula for a low-cost organic electrode material.

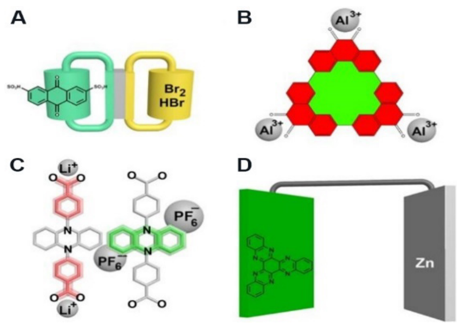

Fig. 1. Formula for the structure of certain inexpensive organic electrode materials. (A) For flow batteries, 9, 10-anthraquinone-2, 7-disulfonic acid. (B) A triangular macrocycle based on phenanthrenequinone that is redox active. Phenazine-5,10-diyl) dibenzoate, 4, 4-. (D) The Zn-organic battery's phenazine component [28].

One of the component parts of current electrodes, cobalt, is categorized as an essential raw material. Processing inorganic minerals is a particularly energy-intensive operation. On the other side, because the biomass may produce new precursors, organic materials may be thermally recycled [18]. Additionally, the organics' real electrochemical performance is not worse. Because of the light elements, they have a large gravimetric capacity and a very high rate of charge and discharge [19, 20]. However, there are still certain issues that need to be resolved, even though organic materials have several advantages as substitute electrode materials in LIBs [21]. Their often low electronic conductivity is a significant obstacle that may restrict the battery's overall performance and rate capabilities [16, 22]. For organic cathode materials, cyclability and stability are also important factors. A shorter battery life and capacity fading can result from some organic compounds' low stability after repeated cycles of charging and discharging [23-25]. Additionally, some organic cathode materials have trouble becoming soluble in the electrolyte. Over time, capacity loss and electrolyte degradation may arise from dissolving the active molecules in the electrolyte [26, 27].

3. Recent advancements in electrode materials

Recent developments in electrode materials have greatly improved energy storage and conversion devices' sustainability and performance [29]. This section briefly overviews current developments in sodium-ion, lithium-ion, and multivalent ion battery electrode materials.

3.1. Lithium-ion batteries (LIBs)

Electrode processing greatly impacts manufacturing cost, throughput, and Cell energy density, which is crucial to developing lithium-ion battery technology. However, there hasn't been nearly as much work done in this field as there has been in materials development [30, 31].

3.1.1. Innovations in anode and cathode materials

Several breakthroughs have been made in lithium-ion batteries' materials used as anodes and cathodes. Table 1 shows some of the innovations in this field.

3.1.2. Role of metal-organic frameworks (MOFs)

In addition to having the functional properties of both an organic ligand guest and a metal ion host, metal-organic frameworks (MOFs), as well as their derivative materials, also provide the benefits of wide surface area, tunable porosity, structure, and composition [49, 50]. Within the energy sector storage, they have excellent application potential when used along with suggestions for electrode material design [51]. MOFs are more ordered than typical materials, and their structural diversity and flexibility can be effectively controlled by the organic ligands and metal ions that may be adjusted. The storage and transfer of lithium ions are made easier by the bigger space and appropriate channel that MOFs' porosity may create [52]. Stable active centers and activity can be created using the component design and nanostructure of MOF composite materials to create effective, long-lasting electrode materials [53]. Nevertheless, MOFs have low conductivity. MOFs must be electrochemically modified in order to enhance their electrochemical characteristics and conductivity [54]. To improve the chemical stability of LIB applications, MOF-derived materials are required to mitigate the disadvantages of MOFs' low conductivity while preserving their advantages [49]. Bai et al. [55] have employed MOFs as dividers in Li–S batteries to reduce shuttling problems (Fig.2). Due to its well-organized micropores, which have a size window of approximately 9 Å, significantly smaller than the diameter of lithium polysulfides, HKUST-1 was selected for this study's MOF@GO separator fabrication. This characteristic contributes to the separator's claimed suitability to block polysulfides and sieve Li selectively ions, with structural stability and reliability observed under electrochemical conditions.

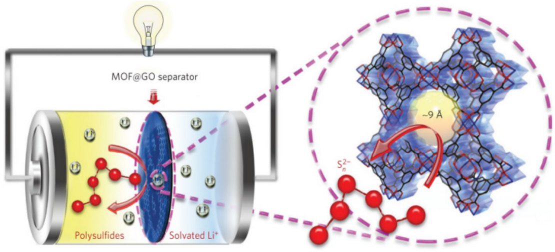

Fig. 2. Schematic diagram of a MOF@GO separator in Li-S batteries [55].

3.2. Multivalent ion batteries

Rechargeable multivalent ion batteries (MIBs) are the best energy storage technology for grid-scale applications because they are less expensive than lithium (Li)-ion batteries [56]. Regarding cost, volumetric energy density, and safety, MIBs that transmit Ca^{2+}, Zn^{2+}, Al^{3+}, Mg^{2+}, and other charge carriers have emerged as an intense research interest. They are becoming more and more appealing options for grid energy storage [57-59]. However, because of the difficulties associated with the restricted multivalent-ion diffusion kinetics, they are still far from becoming mature [59].

3.2.1. Development of organic and inorganic materials

Organic electrode materials (OEMs) are versatile, high-performing electroactive materials used across various rechargeable battery systems because of their availability, ease of use, affordability, sustainability, and recyclability. Advanced rechargeable battery development is made possible by the wide structural variety and the ability to tune OEMs, composed of light components that are abundant on Earth, including H, O, C, S, and N [60-63].

The functional group that is active, not the crystalline structure, determines the electrochemical performance of OEMs, in contrast to inorganic electrode materials. The varied molecular structures and unique electrochemical properties of OEMs contribute to their strong electrochemical performance in lithium-ion batteries (LIBs) and other applications [63, 64].While the energy density of organic energy materials (OEMs) is not yet on par with that of inorganic materials used in lithium-ion batteries (LIBs), their low cost, widespread availability, and structural adaptability make OEMs excellent candidates for affordable and sustainable energy storage solutions [64].

Table 1
Innovations in anode and cathode materials in LIBs.

	Material types	Advantages	Refs.
Innovations in anode materials	Silicon-based anodes	High theoretical capacity but volume expansion challenges	[32-36]
	Carbon-based nanomaterials (graphene, reduced graphene oxide)	Conductivity and stability	[37-39]
	Metal oxides and sulfides (Fe_2O_3, MoS_2)	High theoretical capacity but issues with volume change and conductivity	[40, 41]
	Metal oxide-carbon hybrids	Combining the advantages of both components	[42]
	Mxenes (2D transition metal carbides)	High conductivity and fast lithium-ion transport	[43]
	Perovskite-like hybrid anodes based	High Li storage capacity and tunable properties	[44]
	Electrospun nanofiber anode materials	Improving rate capability and cycling stability	[45]
Innovations in cathode	High voltage spinel cathodes like ($LiNi_xCo_xM_{1-x-y}O_2$)	Offering high rate and energy density	[46, 47]
	Diverse cathode materials explored	Improved voltage and capacity	[48]

3.2.2. Performance comparisons with traditional batteries

Cost and safety are crucial considerations when using battery technology for extensive stationary electrical energy storage. Unfortunately, the high toxicity of Pb/PbO_2 and the scarce and unequally distributed lithium resources hinder the development of LIBs and lead acid batteries (LABs), respectively [16, 65-67]. Many people are looking forward to another advancement in battery technology that will result in energy storage systems that are safe, affordable, and environmentally friendly. Since multivalent metals and OEMs are inexpensive and plentiful, organic multivalent rechargeable batteries (MRBs) are a possible substitute for LIBs and LABs [64].

3.3. Sodium-ion batteries

Similar to LIB, NIB operates by having Na ions move between two electrodes that house Na ions via an organic liquid electrolyte while a voltage is applied [68]. At the laboratory scale, NIBs perform almost as well as commercial LIBs regarding cycle life, power density, and energy density [69-71]. Several layered oxide cathodes, for instance, have been shown to achieve an extended lifecycle of several hundred cycles, a high rate of 30 °C, and a high capacity of 190 mAh g^{-1} [70, 72-74]. Recent NIB research projects showed potential for developing NIB systems that function similarly to LIBs [75].

4. Conclusion

The advancement of efficient energy storage systems has dramatically accelerated due to recent advancements in battery electrode materials. The limitations of conventional materials like graphite have been addressed through innovations in anode and cathode materials, including composites, which have significantly improved energy density, charging speed, and cycle life. Research continues to focus on new synthesis methods, coatings, and targeted doping to tackle challenges related to cost, safety, and resource scarcity. Increased capacities are expected as the industry shifts from traditional intercalation processes to conversion-type reactions; however, further research and engineering will be necessary to ensure stability and longevity. The combination of material innovation and architectural redesign is making next-generation batteries with quicker charging, longer lifespans, and wider applications in electric vehicles, grid storage, and portable gadgets possible. However, more research and scalable manufacturing techniques will be needed to turn these discoveries into economically feasible, effective, and sustainable energy storage technologies.

Author contributions

Naghmeh Abavi Torghabeh: Conceptualization, Writing – original draft, Writing – review & editing; **Mahnaz Dadkhah:** Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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