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Application of nanomaterials for improving zinc-ion batteries performance

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Abstract. Extensive endeavours are underway to devise global strategies for energy storage, aiming to fulfil the burgeoning energy demands in the foreseeable future. While lead-acid batteries (LABs) and lithium-ion batteries (LIBs) are currently two common and widely used types of batteries, they are accompanied by environmental implications and safety apprehensions. In this context, aqueous zinc-ion batteries (AZIBs) have emerged as an up-and-coming solution, exhibiting an economically viable composition and leveraging nanomaterials to enhance electrochemical performance and facilitate efficient energy storage. This passage delves into recent studies about incorporating nanoparticles in rechargeable aqueous AZIBs and evaluates their performance characteristics. A comprehensive analysis of eight studies has been conducted, scrutinizing various aspects such as electrochemical performance, stability, specific capacity, and charging rate. By juxtaposing these studies, noteworthy observations have been made regarding the impact of nanoparticles, along with insights into potential advancements for the AZIBs in the future.

Keywords: Zinc-Ion Batteries, Nanomaterials, Electrochemical Performance.

1. Introduction

Developing global energy storage strategies to fulfil our energy requirements is soon receiving more attention, finding an efficient method to store intermittent energy sources like wind, tidal, and solar power. To supersede traditional fossil energy, lead-acid batteries (LABs) and lithium-ion batteries (LIBs) are nowadays credited to be the most classic examples leading the primary market of energy storage and power drives. However, overuse of soluble lead in LABs can cause adverse effects on the environment. Even though LIBs have been improved by a robust quality control procedure under tremendous efforts, latent defects of LIBs in structural and chemical characteristics could still bring about severe outcomes like acute failure or chronic degradation [1]. Besides, problems concerned with safety also lie in unstable organic electrolytes. Therefore, cost-effective and safe metal-based aqueous secondary batteries and environmentally friendly electrolytes are crucial to transforming the battery market as promising candidates in the future [2].

Recently, aqueous zinc-ion batteries (AZIBs) are gradually being widely used due to their excellent electrochemical performance, making them an excellent choice for energy storage. Zinc shows high theoretical capacity low redox potential, and favourable reversibility of Zn^{2+}/Zn. This allows fabrication to be conducted in ambient conditions without needing a glove box environment [3]. The emerging fields of nanotechnology can provide a revolutionary opportunity to achieve clean energy utilization and to improve electrochemical reactivity. Specifically, AZIBs with nanostructures in their electrodes, electrolytes, and exchange membranes can exhibit superior electrochemical performance compared to conventional batteries [4]. These nanostructured active materials have the potential to surpass their corresponding bulk forms due to their ability, such as more active sites and structural flexibility [5].

As a result, this research aims to provide a comprehensive summary and comparison of the electrochemical effects resulting from the application of various nanomaterials in the AZIBs. Specifically, the focus will be on analyzing the performance and kinetics of the electrode and electrolyte. By examining the advancements made in these specific areas, valuable insights can be gained regarding the potential of nanomaterials to optimize the overall performance of AZIBs. Through an in-depth analysis, this can provide ideas for future research.

2. Application of nanomaterials in AZIBs

2.1. Bi-Continuous metallic zinc nanoporous electrodes

A zinc nanoporous electrode can be designed and further used to stabilize the electrochemical transition between metallic Zn and ZnO. The nanoporous zinc electrodes demonstrated promising energy storage performance. By optimizing electrochemical testing conditions, the developed nanoporous zinc electrodes operated optimally for 80 hours in lean electrolyte conditions. However, this research did not mention specific details regarding capacity retention or efficiency over time.

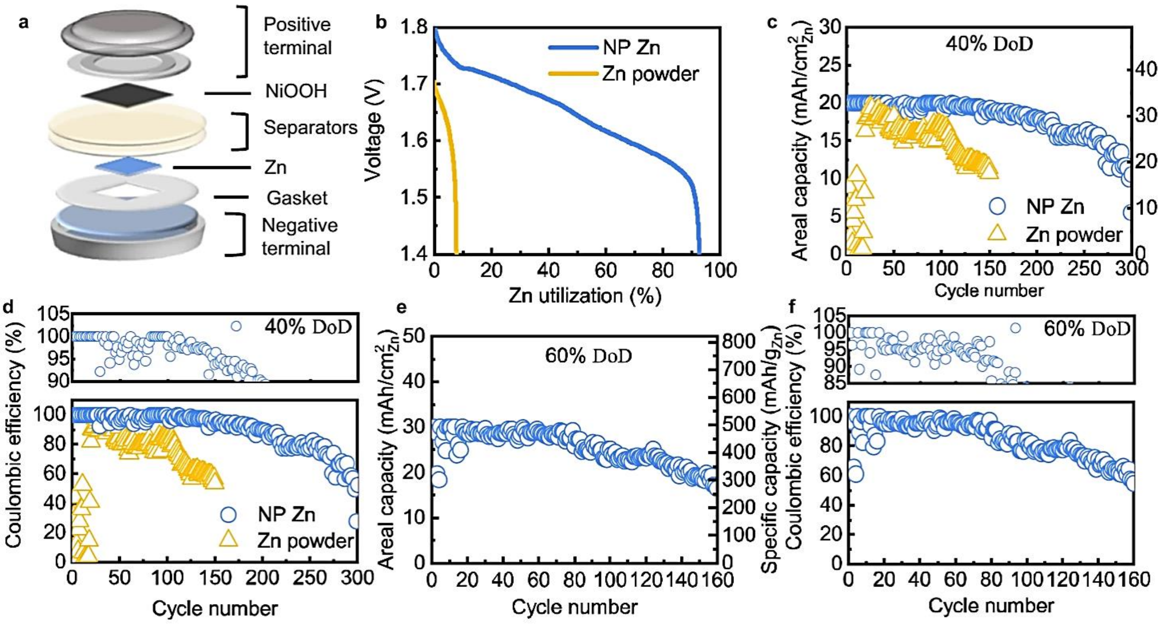

Figure 1. The electrochemical performance of whole cells consisting of Zn and NiOOH is being studied [6]. (a) schematic of Zn||NiOOH coin cell used in this study. (b) Examining the utilization of zinc in various anodes for primary Zinc/Nickel Hydroxide alkaline batteries. (c) Discharging capacities of the NP Zn and Zn powder anodes at 40% DoD vs. the cycle number. (d) Efficiency of Zn nanoparticles and powder in lean electrolyte at 40% DoD, with an extra y-axis for an initial 100 cycles. (e) and (f) discharge capacities and efficiency of NP Zn anode at 60% DoD, including efficiency in the first 100 cycles.

It is fascinating to note the remarkable resilience of the porous Zn anode, even when subjected to high levels of depth of discharge (DoD). The open-circuit voltage of the NP Zn anode remains consistent, in contrast to the Zn powder anode, suggesting that cell cycling cannot be impacted by hydrogen evolution, as shown in Figure 1. This positive development highlights the potential of the porous Zn anode for advancing energy technology. Thus, the application of nanoporous zinc electrodes can stabilize the electrochemical reaction [6].

The study's findings indicate that excessive battery discharge (beyond 40% depth of discharge) can adversely affect NP Zn and ZnO growth and reduction. When exposed to oxygen, the Zn network can disintegrate, causing a decline in electrical conductivity as it transforms into ZnO. This can result in electrode instability and other battery-related problems that can be severe. Additionally, ZnO growth can impede mass transport in the pores, decreasing porosity and increasing tortuosity due to its irregular shape, eventually leading to the battery's collapse.

2.2. Zinc-manganese oxide batteries

A solution is proposed to address the rapid capacity decay of $ZnMn_2O_4$ (ZMO) at high rates. The solution involves synthesizing ZMO nanoparticles, which are approximately 20 nm in size, on a carbon nanotubes (CNTs) heterostructure. It exhibits excellent recyclability in a ZMO battery. Moreover, flexible ZIBs assembled under the CNTs network structure and the strong interface interaction between ZMO and CNTs show stable electrochemical properties [7]. This approach provides a rational synthesis method for durable high-rate Zn^{2+} storage, addressing the deficiency of ZMO in rapid capacity decay at high rates. The unique structure of the ZMO/CNTs composite improves ions/electrons transport and prevents structural degradation.

2.3. N/Se-MXene@ZnSe composite anodes

A zincophilic layer based on the N/Se-doped MXene nanomaterials and ZnSe nanoparticles can be used to enable uniform zinc deposition and prevent side reactions. The optimized anode based on this zincophilic layer demonstrates stable zinc deposition, low voltage hysteresis, and good recyclability. At the same time, the entire cell configuration maintains stable performance with high Coulombic efficiency. A ZnSe nanoparticle film, composed of electronic and ionic elements, was used. The designed cell had low voltage hysteresis and lasted 2500 hours. It showed better stability at high rates, with improved recyclability and fast kinetics processes [8].

It's important to know that when Zn foil is modified and heated to 400 °C, it can become structurally deformed and damaged due to its low melting point. As a result, the damaged Zn foil cannot be used as an anode in ZIBs. This means the thermal treatment at 400 °C is not the best choice for excellent battery performance. The device was maintained at a distance of 4 cm and returned to its baseline readings, albeit with a delay of 10^{-2} and 2^{-2}, respectively. Similarly, after 250 hours of usage, the voltage hysteresis was found to have amplified, indicating a decrease in stability. The developed anode appears to have underperformed, potentially due to the ZnSe nanoparticles being too diminutive to accommodate adequate zinc-loving sites. Consequently, the deposition of zinc proved to be uneven when subjected to high current density. However, the developed anode exhibits superior structural attributes.

2.4. V_2O_5/GO heterojunction nanomaterials

A recent scientific study has unveiled a significant breakthrough in battery technology. Researchers have discovered that incorporating graphene oxide (GO) into vanadium pentoxide (V_2O_5) nanostructures can significantly enhance the ZIBs' performance.

Through the meticulously designed synthesis process, V_2O_5 nanoparticles were synthesized on GO plates, creating a V_2O_5/GO heterojunction. This heterojunction effectively facilitated electron transfer and improved electrolyte accessibility within the battery structure, thereby bestowing exceptional advantages upon the V_2O_5/GO-ZIBs. These advantages include high specific capacity, remarkable stability, groundbreaking fast-charging capability, and impressive rate capabilities. Incorporating GO into V_2O_5 nanostructures establishes efficient electron pathways within the ZIBs, leading to the realization of batteries with unparalleled performance characteristics. Notably, the V_2O_5/GO-ZIBs exhibit an outstandingly long lifespan of 10,000 cycles, retaining 90.8% of their initial capacity. This remarkable performance exceeds that of most other reported V-cathodes.

Moreover, the V_2O_5/GO-ZIBs showcase an additional noteworthy attribute: they demonstrate unprecedented fast-charging ability. Voltage/current-time curves depicted in Figure 4a illustrate their capability to attain a full charge in a mere 12.8 seconds at 40 A/g. This astounding speed equates to the battery reaching total capacity instantly, setting a new standard for rapid charging. The V_2O_5/GO-ZIBs exhibit remarkable stability during rapid charging and discharging. This is demonstrated in Figure S5a-b, which showcases consistent voltage changes over 1 hour and 1000 cycles, emphasizing the excellent reversibility of these batteries. As a result, they consistently deliver reliable performance, demonstrating their resilience under demanding conditions [9].

This breakthrough study holds immense potential for the future of battery technology, particularly in electric vehicles. The superior performance, extended lifespan, and unprecedented fast-charging capability of V_2O_5/GO-ZIBs signify a notable advancement in energy storage, promising more efficient and powerful battery solutions.

The V_2O_5/GO-ZIB composite shows a specific capacity of 115 mAh and a device mass of 4g. It is stable and performs consistently over 1000 cycles, with only a slight decline of 1. These properties of V_2O_5 nanomaterial make it an up-and-coming option for energy storage in academic and commercial applications. The V_2O_5/GO structure displays lower resistances, suggesting that GO enhances the conductivity of the composite. As a result, electron transport within the active materials is smoother, and Zn^{2+} ions diffuse more quickly in both the electrode and electrolyte. The increased capacitive contributions enable substantial zinc ion storage on the surface of the V_2O_5/GO, which reduces lattice collapse and promotes quick Zn^{2+} transfer and structural stability. These elements align with the observed high-performance and extreme-fast charging capabilities.

2.5. *CuV_2O_6 nanobelts as game-changing cathode materials*

The CuV_2O_6 nanobelts (CVO NBs) can be used to design new AZIBs. The study highlights the significant impact of removing metallic Cu on enhancing electric conductivity, ultimately leading to exceptional electrochemical performance due to the stable structure of CVO NBs. These findings demonstrate the potential of CVO NBs as a promising candidate for cathode materials in AZIBs. Due to the ability of graphene oxides (GO) to capture tremendous oxygen inside, wrapping GO nanosheets in Cu V_2O_6 nanocomposite (GO-CVO NBs) can be realized. Thus, Cu V_2O_6 is a promising candidate for cathodes in AZIBs for grid-scale ESDs due to its high specific capacity, good recyclability and high-rate performance. The article designs high-performance rechargeable AZIBs with excellent stability [10].

The original capacities of the battery can be effectively restored by fluctuating current flow. This process serves to demonstrate the inherently convincing structural stability of the battery. Through electron microscopy characterization, the results show that a slight formation of BZS occurs on the CVO NWs surface during discharge, as shown in Figure 2. However, upon recharging, this BZS promptly dissipates without causing any harm to the CVO nanostructure. These observations further validate that the CVO NWs are an immensely stable ZIB cathode. The mechanism by which BZS is formed in ZIBs is not currently well-established.

2.6. *$(NH_4)_2V_3O_8$: Unleashing the Potential of a Layered Nanomaterial*

The article proposes the structure of $(NH_4)_2V_3O_8$, which consists of layers of V_3O_8 and NH_4^+ ions. This structure effectively stores Na^+ and Li^+ ions in SIBs and LIBs. $(NH_4)_2V_3O_8$/C can be also used to prepare ARZIBs with excellent cycling stability and high energy density. When utilized as the cathode in ARZIBs, it is important to note that it functions within a potential range of 0.4–1.6 V, in contrast to Zn^{2+}/Zn [11]. These findings showcase the potential of $(NH_4)_2V_3O_8$/C as an electrode material for advanced rechargeable ZIBs. And $(NH_4)_2V_3O_8$ exhibits a unique layered structure, where this arrangement forms sheets parallel to the (001) direction, contributing to the battery's excellent performance.

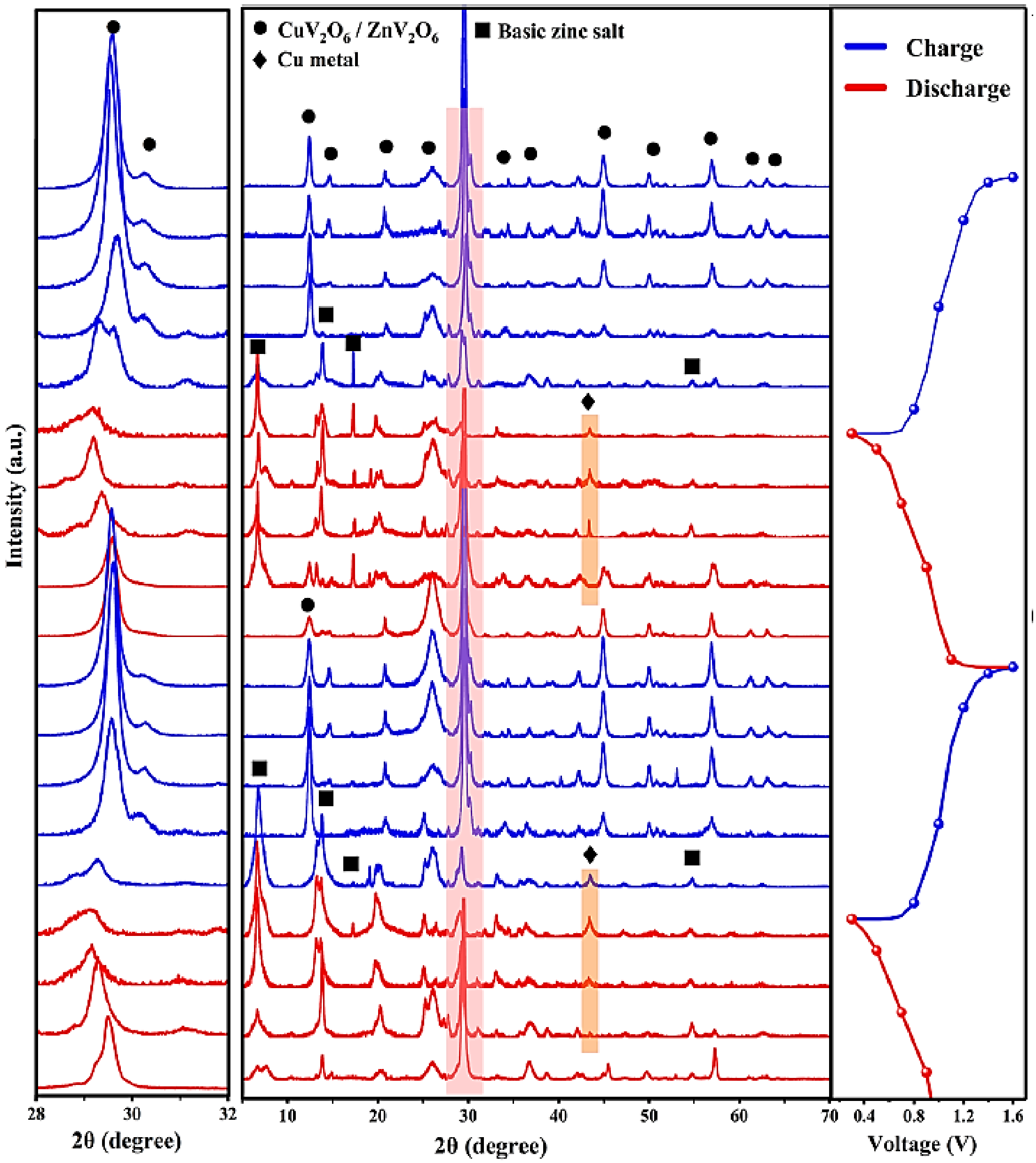

Figure 2. The XRD patterns of the CuV_2O_6 cathode in a Zn/CuV_2O_6 battery with $Zn(CF_3SO_3)_2$ electrolyte gathered during the first two cycles at different electrochemical states [10].

2.7. *Carbon-coated manganese oxide cathodes*

This passage pertains to the application of conductive carbon-coated manganese oxide as the cathode in ZIBs. This battery is further reinforced by a porous carbon framework, resulting in a substantial specific surface area. The battery technology exhibits immense potential for numerous applications that require a dependable and high-performing power source. This innovation can significantly enhance the capabilities of battery-powered devices, facilitating more efficient performance. The analysis revealed that a high specific surface area for porous carbon is a significant factor. The cathode made of $C\text{-}MnO_2$ has demonstrated a remarkable capacity of 234 mAh/g with consistent coulombic efficiency and impressive rate performance, and it also shows excellent recyclability, as shown in Figure 3.

Similar to the C-O-Mn and C-O-H bonds, the C-S bond exhibits a degree of persistence following the second charge. The observed peak intensity ratio, which stands at approximately 1:0.63, supports the notion that adsorption and ion de-insertion occur concurrently within the porous carbon layer [12]. Surface scans have revealed the detection of nitrogen. Current research suggests that the incorporation of nitrogen into carbon can significantly improve cycling performance.

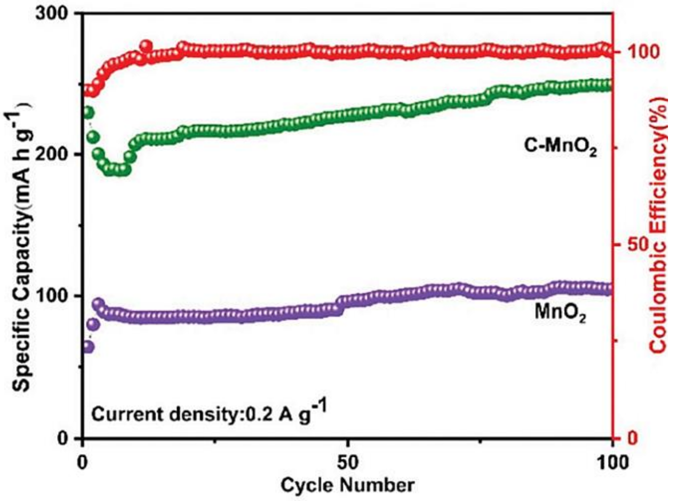

Figure 3. Cycle performance and coulombic efficiency [12].

3. Conclusion

In conclusion, exploring various Zinc-ion batteries in this study has revealed promising advancements in battery performance. Incorporating unique electrode structures, zincophilic layers, and graphene oxide has significantly improved storage, stability, lifespan, fast-charging capability, and specific capacity. These findings offer insights into the future trends in zinc-ion battery development and hold implications for the broader application of energy storage technologies. Furthermore, strategies such as metallic Cu stripping, $(NH_4)_2V_3O_8$ structure, and C-MnO_2 cathode have shown remarkable achievements in high energy density, cycling stability, and rate performance. These results highlight the vast potential of zinc-ion batteries to address the challenges facing current energy storage systems. Advancements in this technology could accelerate the transition to renewable energies by delivering a scalable and sustainable solution to long-term energy storage. Overall, the findings provide a solid foundation for further exploration and development of Zinc-ion batteries. Future research should address existing limitations and maximize the potential of nanoparticles and nanostructures to unlock the full capabilities of zinc-ion battery technology.

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