academic publishers

INTERNATIONAL JOURNAL OF MECHANICAL ENGINEERING (ISSN: 2693-3713)

Doi: - https://doi.org/10.55640/ijme-05-01-02

Volume 05, Issue 01, 2025, pages 08-17 Published Date: - 31-03-2025

Exploring Aqueous Zinc-Based Batteries: From Active Materials to Future Applications

Daniel Sinclair

Department of Mechanical and Industrial Engineering, University of Toronto, Canada

Abstract

Aqueous zinc-based batteries (AZBs) have gained significant attention as a promising alternative to conventional lithium-ion batteries due to their advantages of safety, low cost, and environmentally friendly operation. These batteries utilize aqueous electrolytes, making them inherently safer and easier to manufacture. However, challenges remain in improving their electrochemical performance, including issues related to dendrite growth, limited energy density, and cycle life. This review article provides an overview of the active materials used in AZBs, highlighting recent advancements in cathode and anode materials. We also discuss key aspects of device design, including electrolyte optimization, separator development, and system integration. Finally, the paper explores future directions for the development of AZBs, including strategies to enhance performance, improve cycle stability, and scale up production for commercial applications.

Keywords

3D printing, Artificial limbs, digital restoration, Structural forecasting, accessibility, additive manufacturing, personalized healthcare, computational modeling, mechanical testing, cost-effective Artificial limbs.

INTRODUCTION

Aqueous zinc-based batteries (AZBs) have emerged as an attractive alternative to conventional lithium-ion batteries (LIBs) due to their inherent safety, low cost, and environmentally friendly nature. As the demand for efficient, sustainable energy storage systems grows—driven by the increasing use of renewable energy sources, electric vehicles (EVs), and portable electronics—there is an increasing need for safe and cost-effective batteries that can meet these requirements. Zinc, as an anode material in AZBs, stands out as an ideal candidate because of its high abundance, low toxicity, and relatively high theoretical capacity (820 mAh/g), which is significantly greater than that of other commonly used metals such as lead and sodium. Additionally, aqueous electrolytes are generally non-flammable, posing a lower risk of fire or explosion compared to the organic solvents used in LIBs.

The development of AZBs is fueled by the desire for safer and more sustainable energy storage systems. While LIBs have revolutionized energy storage and are widely used in portable electronic devices and EVs, they come with concerns over material scarcity (such as lithium and cobalt), environmental impact, and safety issues such as flammability and thermal runaway. In contrast, zinc is abundant and inexpensive, making it a more sustainable option. Furthermore, AZBs, by utilizing aqueous electrolytes, minimize the environmental impact and safety risks associated with organic solvents, which are flammable and toxic. This unique combination of zinc as an anode material and aqueous electrolytes offers AZBs a clear safety advantage over other battery technologies.

However, despite the promising advantages, the commercialization of AZBs has been hindered by several challenges, notably the issues related to dendrite formation, low energy density, and relatively poor cycle life. Dendrite growth on the zinc anode

during charge-discharge cycles is one of the most significant challenges that can lead to short-circuiting, reduced efficiency, and ultimately battery failure. As zinc ions are plated onto the anode during charging, non-uniform deposition can result in the growth of dendrites, which can puncture the separator and lead to internal short circuits. Additionally, the energy density of AZBs is lower compared to lithium-based systems, which limits their application in energy-intensive devices, such as electric vehicles (EVs) and large-scale energy storage systems.

In recent years, there has been significant progress in addressing these challenges. Researchers have explored a variety of strategies to mitigate dendrite formation, such as the development of protective coatings for zinc anodes, optimization of electrolyte compositions, and the introduction of novel separator materials. Advances in cathode materials have also played a key role in enhancing the performance of AZBs. Transition metal oxides, including manganese dioxide (MnO2) and vanadium oxide (V2O5), are the most widely researched cathode materials, but their performance can degrade over time. Recent research has focused on improving the stability and capacity retention of these cathodes by using composite materials or exploring new materials with superior electrochemical properties.

Despite these advancements, the energy density of AZBs remains a major limitation, particularly for high-performance applications like EVs. However, new developments in hybrid battery technologies, such as integrating AZBs with other battery types (e.g., lithium or sodium-ion), or the use of novel polyanionic or organic cathodes, are helping to improve the overall energy density and performance of AZBs. Moreover, the potential for scaling up AZBs for large-scale grid energy storage has generated significant interest, as they can provide long-duration energy storage with lower cost and enhanced safety compared to current technologies.

This review provides a comprehensive overview of the recent advancements in aqueous zinc-based batteries, focusing on active materials, device design, and future prospects. We first explore the role of zinc anodes and the strategies employed to mitigate dendrite formation and enhance cycle life. Next, we examine the development of cathode materials, highlighting both traditional and emerging materials for AZBs. The design and optimization of the battery system—including electrolyte formulation, separator materials, and cell architecture—are discussed in detail, with an emphasis on how these factors influence the overall performance. Finally, we look forward to the future directions in AZB research, including strategies to further improve energy density, cycle stability, and scalability for commercial applications. By addressing the current limitations and continuing to innovate in material science and battery design, AZBs have the potential to play a critical role in the transition to a more sustainable and safe energy storage system.

Aqueous zinc-based batteries (AZBs) have emerged as a promising candidate for next-generation energy storage devices due to their safety and environmental benefits. Zinc, as an anode material, is particularly attractive because it is abundant, non-toxic, and has a high theoretical capacity (820 mAh/g), which is significantly higher than that of many other commonly used anode materials, such as lead and lithium. Furthermore, AZBs operate in aqueous electrolytes, which further enhances their safety by eliminating the flammability risks associated with organic electrolytes in lithium-ion batteries (LIBs).

Despite these advantages, AZBs face several challenges that need to be addressed before they can be widely adopted. One of the most critical issues is the formation of zinc dendrites, which can lead to short-circuiting and reduced cycle life. Additionally, the energy density of AZBs is still lower than that of LIBs, limiting their application in energy-dense devices such as electric vehicles (EVs). This paper reviews recent advancements in AZB research, focusing on improvements in active materials, device design, and the potential for commercialization.

METHODS

1. Active Materials in Aqueous Zinc-Based Batteries

The performance of AZBs is heavily influenced by the choice of active materials for both the anode and cathode. In this section, we discuss the latest developments in active materials, particularly focusing on the challenges of achieving high energy density and stable cycling performance.

1.1. Zinc Anode Materials

Zinc metal is the most commonly used anode material in AZBs due to its high theoretical capacity, low cost, and non-toxicity. However, zinc's tendency to form dendrites during charging, which can cause short-circuiting and cell failure, remains a significant challenge. Recent research has focused on mitigating dendrite growth by modifying the zinc anode with protective coatings, such as carbon-based materials, polymers, or metal oxides. Additionally, optimizing the electrolyte composition and developing novel electrolytes has been shown to improve the stability of the zinc anode and suppress dendrite formation.

1.2. Cathode Materials

The choice of cathode materials in AZBs is equally important for improving their performance. Traditionally, cathodes based on

manganese dioxide (MnO_2), vanadium oxide (V_2O_5), and other transition metal oxides have been used. These materials provide high voltage output but suffer from poor cycle life and capacity fading. More recently, researchers have focused on developing composite materials and exploring novel cathode chemistries, such as polyanionic compounds, that exhibit high stability and capacity retention. Additionally, the development of cathode materials that are highly conductive and can effectively utilize the available charge in aqueous environments is a key focus area for improving the overall performance of AZBs.

2. Device Design and Optimization

The overall performance of AZBs depends not only on the active materials but also on the design and optimization of the battery system. Key factors such as the electrolyte formulation, separator design, and the overall architecture of the battery have a significant impact on its efficiency, energy density, and cycle stability.

2.1. Electrolyte Development

Aqueous electrolytes play a crucial role in determining the performance of AZBs. The development of non-corrosive, high-conductivity electrolytes that can maintain a stable pH range and prevent side reactions is essential. The most commonly used electrolyte in AZBs is zinc sulfate ($ZnSO_4$), which allows for efficient zinc deposition and dissolution. However, research into alternative electrolytes, such as those based on zinc chloride ($ZnCl_2$), zinc acetate ($Zn(CH_3COO)_2$), and other zinc salts, has demonstrated the potential to improve the battery's performance. Innovations in the electrolyte composition, such as the use of additives that can suppress the formation of dendrites, are also important for improving the cycle life and safety of AZBs.

2.2. Separator Materials

The separator in AZBs must serve as a barrier between the anode and cathode, preventing short circuits while allowing for the efficient flow of ions. Traditional separators, such as polyethylene (PE) and polypropylene (PP), have been used in AZBs, but they suffer from low ionic conductivity and poor mechanical stability. Recent research has focused on the development of novel separators, including those made from conductive polymers, graphene oxide, and ceramic-based materials, to enhance the ion transport and mechanical integrity of the separator.

3. Scaling Up and Commercialization

While much of the research on AZBs has focused on laboratory-scale devices, scaling up these technologies for commercial applications is critical for realizing their full potential. Challenges include optimizing the manufacturing process, reducing material costs, and ensuring the long-term stability and reliability of the battery under real-world conditions. The integration of AZBs into energy storage systems for grid-scale applications and electric vehicles (EVs) holds significant promise, but further advancements in performance and cost-effectiveness are needed before these batteries can compete with existing technologies.

RESULTS

Recent advancements in active materials and device design have led to significant improvements in the performance of aqueous zinc-based batteries. For example, modifications to the zinc anode, such as the introduction of protective coatings or the use of optimized electrolytes, have successfully reduced dendrite formation and improved the cycling stability of the battery. Similarly, the development of advanced cathode materials, such as composite MnO_2 and V_2O_5-based electrodes, has led to enhanced capacity retention and longer cycle life.

In terms of device design, optimized electrolytes have demonstrated improvements in conductivity and stability, with novel formulations reducing side reactions and enhancing performance under high charge-discharge rates. Additionally, the introduction of advanced separators has improved the overall ionic conductivity and mechanical stability of AZBs, leading to better cycle life and efficiency.

Despite these advancements, challenges remain. The energy density of AZBs is still lower than that of lithium-ion batteries, limiting their potential applications in energy-intensive sectors like electric vehicles. However, with continued research into new active materials, electrolyte formulations, and device architectures, AZBs are expected to evolve into a viable alternative for various stationary and portable energy storage applications.

DISCUSSION

Aqueous zinc-based batteries (AZBs) have demonstrated great potential as a safer, more cost-effective, and environmentally friendly alternative to conventional lithium-ion batteries (LIBs). As the demand for sustainable energy storage solutions increases, AZBs are becoming increasingly attractive due to their use of abundant and non-toxic materials like zinc and the use of aqueous electrolytes, which mitigate safety risks such as flammability. However, despite these promising advantages,

significant challenges remain that hinder their widespread commercialization. In this section, we discuss the key limitations of AZBs, including dendrite formation, energy density, and cycle stability, as well as recent advancements aimed at addressing these issues.

1. Dendrite Formation in Zinc Anodes

One of the primary challenges in aqueous zinc-based batteries is the formation of zinc dendrites during cycling, which can significantly reduce the performance and lifespan of the battery. Zinc dendrites grow during the charging process when zinc ions are deposited on the anode, but if the deposition is uneven, it leads to the growth of needle-like structures (dendrites) that can pierce the separator and cause short circuits. This not only compromises the safety of the battery but also leads to rapid capacity degradation and eventual failure of the cell.

Several strategies have been developed to mitigate dendrite formation in zinc anodes. One promising approach is the modification of the anode with protective coatings. Researchers have investigated the use of carbon-based materials (e.g., graphene oxide, carbon nanotubes), polymers, and metal oxides to form a stable, uniform layer on the zinc surface that promotes even deposition and inhibits dendrite growth. For example, carbon-based materials can act as conductive buffers that facilitate the uniform plating of zinc and prevent the concentration of zinc ions at certain sites on the anode. Similarly, the application of polymer coatings, such as polyvinyl alcohol (PVA) or polyvinylidene fluoride (PVDF), has been shown to improve the mechanical properties of the anode, thus preventing the growth of dendrites.

In addition to coatings, modifying the electrolyte composition has also shown promise in controlling dendrite formation. By adjusting factors such as the concentration of zinc salts, pH level, and the presence of additives, researchers have successfully enhanced the stability of the zinc anode. For instance, certain additives, such as chloride ions or organic compounds, can help regulate the deposition of zinc and prevent the formation of dendrites. Thus, controlling both the anode surface and electrolyte chemistry is crucial to addressing the dendrite problem in AZBs.

2. Energy Density Limitations

While zinc has a high theoretical capacity (820 mAh/g), the energy density of AZBs remains lower than that of lithium-ion batteries. The relatively low energy density of AZBs is mainly due to the limited voltage window of the aqueous electrolyte, which restricts the overall cell voltage and thus the energy output. The energy density of AZBs typically ranges from 100 to 150 Wh/kg, which is significantly lower than that of LIBs, which can exceed 250 Wh/kg.

Improving the energy density of AZBs is one of the key challenges facing researchers. One strategy to enhance energy density is the development of new cathode materials. Traditional cathodes, such as manganese dioxide (MnO_2) and vanadium oxide (V_2O_5), offer high voltage but suffer from poor cycle life and limited capacity retention. To address these issues, researchers are focusing on developing composite cathodes that combine high-capacity materials with conductive polymers or carbon-based materials to improve both capacity and stability. For example, MnO_2 combined with graphene oxide has shown improved conductivity and cycle stability, allowing for better utilization of the active material during cycling.

Another approach to enhancing energy density is the use of alternative cathode chemistries that can operate at higher voltages. Polyanionic compounds, such as phosphates, have gained attention due to their ability to offer high voltage while maintaining good stability. In addition, hybrid cathodes that combine aqueous-based and solid-state materials have also been proposed to increase the operating voltage and overall energy output of AZBs. These hybrid systems, although still in the early stages of development, hold great potential for improving the energy density of AZBs while maintaining their safety and environmental advantages.

Furthermore, optimizing the electrolyte composition and separator design can help to enhance the energy density. The use of non-aqueous electrolytes or gel-based electrolytes, while more challenging due to stability concerns, could potentially expand the voltage window and improve the energy density of AZBs. Similarly, the development of more efficient separators that allow for better ion transport and less internal resistance could enhance the overall performance of AZBs, leading to a higher energy density.

3. Cycle Life and Stability

In addition to dendrite formation and energy density, the cycle life and long-term stability of AZBs remain areas of concern. The cycling performance of AZBs is often compromised by issues such as zinc dissolution, side reactions at the cathode, and the degradation of the electrolyte. These factors can lead to a gradual loss of capacity, poor coulombic efficiency, and reduced cycle life.

To address these issues, researchers have focused on improving the stability of the zinc anode. One approach is to modify the electrolyte to prevent the dissolution of zinc ions during cycling. For instance, by adding agents such as surfactants or polymers

to the electrolyte, zinc dissolution can be minimized, and the zinc surface can be protected. Similarly, the development of hybrid electrolytes that combine aqueous and non-aqueous components has shown promise in improving the stability of the battery and enhancing its cycle life.

The cathode material also plays a critical role in the overall stability of the battery. While traditional manganese dioxide-based cathodes are widely used, they suffer from capacity fading due to the dissolution of manganese ions in the electrolyte. Composite cathodes that incorporate stable conductive materials, such as carbon nanotubes or graphene, have been developed to improve the cycle stability of the cathode and reduce the loss of active material. Additionally, the development of more stable cathode materials, such as polyanionic compounds or organic materials, has the potential to improve the overall cycling stability and longevity of AZBs.

4. Scalability and Commercialization

While AZBs show promise in laboratory-scale studies, there are still significant challenges associated with scaling up these systems for commercial applications. For large-scale energy storage solutions, such as grid-scale storage or electric vehicles, AZBs must meet certain performance and cost criteria, including high energy density, long cycle life, and low manufacturing costs. Additionally, the large-scale manufacturing process must be efficient and environmentally friendly.

The commercialization of AZBs will require the development of cost-effective manufacturing techniques, such as scalable electrode production and optimized cell assembly. Moreover, it will be essential to establish standardized performance metrics and ensure that the technology is compatible with existing infrastructure. As AZBs continue to develop, they may be particularly well-suited for stationary energy storage applications, where cost and safety are prioritized over energy density, such as in large-scale renewable energy integration and grid storage systems.

FUTURE DIRECTIONS

The future of aqueous zinc-based batteries lies in the continued optimization of materials, device design, and manufacturing processes. Key areas for future research include:

1. Dendrite-Free Zinc Anodes: Developing advanced coatings and electrolyte additives to fully eliminate dendrite formation and enhance the long-term stability of zinc anodes.

2. High-Energy Cathodes: Further development of high-capacity and high-voltage cathode materials, such as hybrid materials and organic compounds, that can increase the energy density of AZBs.

3. Improved Electrolytes: The development of new electrolyte systems that can widen the voltage window, improve ionic conductivity, and suppress side reactions.

4. Scalable Manufacturing: Advancing the techniques for large-scale production of AZBs while reducing costs and ensuring consistency and performance across large batches.

By addressing these challenges, aqueous zinc-based batteries could become a competitive alternative to lithium-ion batteries for applications that prioritize safety, cost, and environmental sustainability, particularly in large-scale energy storage systems and renewable energy integration.

Aqueous zinc-based batteries present a promising alternative to current lithium-ion battery technology due to their safety, low cost, and environmentally friendly operation. While there are still significant challenges, such as dendrite formation, limited energy density, and cycle life, recent advancements in active materials, electrolyte chemistry, and device design have shown encouraging improvements in the performance and stability of AZBs. Continued research and innovation are needed to further address these challenges and unlock the full potential of AZBs in commercial energy storage applications, with a particular focus on scaling up for grid-scale energy storage and sustainable energy systems.

Aqueous zinc-based batteries represent a promising avenue for the development of safer and more sustainable energy storage technologies. While significant progress has been made in improving the electrochemical performance and stability of AZBs, several challenges still need to be addressed for their widespread adoption. The prevention of dendrite formation in zinc anodes, the development of high-performance cathodes, and the optimization of electrolytes remain key areas of focus.

The low energy density of AZBs compared to lithium-ion batteries is one of the major limitations, but ongoing research into new cathode materials, hybrid battery configurations, and advanced electrolytes may help bridge this gap. Additionally, the potential for AZBs to be integrated into grid-scale energy storage systems and provide long-duration storage solutions is an exciting area of future research.

In conclusion, the development of aqueous zinc-based batteries has the potential to revolutionize the energy storage landscape by offering a safer, more sustainable alternative to current battery technologies. Further advancements in materials, device design, and system integration will be crucial for overcoming the remaining challenges and bringing AZBs to market.

CONCLUSION

Aqueous zinc-based batteries are a promising alternative to conventional energy storage systems due to their safety, low cost, and environmentally friendly operation. Despite challenges such as dendrite formation and lower energy density compared to lithium-ion batteries, recent advancements in active materials, device design, and electrolyte formulations have shown significant improvements in performance and stability. With continued research and innovation, AZBs hold the potential to play a key role in the future of energy storage, particularly in grid-scale applications and for stationary energy storage systems.

Table 1: Comparison of Anode Materials in Aqueous Zinc-Based Batteries

Anode Material	Theoretical Capacity (mAh/g)	Advantages	Challenges
Zinc (Zn)	820	Abundant, non-toxic, low cost	Dendrite formation, zinc dissolution, limited cycle life
Zinc-Alloy Composites	600–700	Enhanced stability, improved performance	Reduced capacity compared to pure zinc
Zinc Oxide (ZnO)	400	High stability, reduced dendrite formation	Lower capacity than zinc metal
Zinc-Based Alloys (e.g., Zn-Mn, Zn-Fe)	500–650	Reduced dendrite growth, increased cycle stability	Complex fabrication process, reduced energy density

Table 2: Cathode Materials for Aqueous Zinc-Based Batteries

Cathode Material	Theoretical Capacity (mAh/g)	Voltage (V)	Advantages	Challenges
Manganese Dioxide (MnO_2)	120–150	1.2–1.6	High voltage, inexpensive, widely available	Poor cycle life, capacity fading, manganese dissolution
Vanadium Oxide (V_2O_5)	300	1.5–2.0	High capacity, high voltage, good stability	Poor conductivity, difficult to synthesize in aqueous media

Polyanionic Compounds (e.g., Phosphates)	150–200	2.0–2.5	High voltage, good stability, long cycle life	Lower conductivity, complex synthesis process
Transition Metal Sulfides (e.g., MoS2)	200–300	1.5–2.2	High capacity, excellent electronic conductivity	Poor cycle stability, sensitivity to side reactions

Table 3: Common Electrolyte Systems for Aqueous Zinc-Based Batteries

Electrolyte Composition	**Ion Conductivity (mS/cm)**	**pH Range**	**Advantages**	**Challenges**
Zinc Sulfate (ZnSO4)	25–40	4–6	High ionic conductivity, stable cycling behavior	Zinc dissolution, dendrite formation under high current
Zinc Chloride (ZnCl2)	30–45	3–5	High conductivity, better cycle stability than ZnSO4	Corrosion of electrodes, side reactions at high voltage
Zinc Acetate (Zn(CH3COO)2)	20–30	4–7	Less corrosive, good for long-cycle stability	Lower ionic conductivity than other electrolytes
Hybrid Electrolytes (e.g., ZnSO4 + additives)	35–50	4–6	Enhanced stability, improved dendrite suppression	Complex formulation, limited commercialization

Table 4: Performance Metrics of Aqueous Zinc-Based Batteries

Battery Type	**Energy Density (Wh/kg)**	**Capacity Retention (%) after 100 Cycles**	**Cycling Stability (Cycles to 80% Capacity)**	**Current Density (mA/cm²)**
Standard Zn-MnO2 / ZnSO4 System	100–120	85–95	200–400 cycles	1–5
Zn-V2O5 / ZnSO4 System	130–150	80–90	250–500 cycles	1–3
Zn-MnO2 / ZnCl2 System	90–110	80–90	100–250 cycles	1–4

Hybrid Zn-Phosphate / ZnSO4 System	140–180	90–98	300–600 cycles	0.5–2

Table 5: Challenges and Solutions in Aqueous Zinc-Based Battery Development

Challenge	Current Impact	Proposed Solutions
Dendrite Formation	Major cause of short-circuiting, reduced battery life	Protective coatings on anode (e.g., carbon, polymers), electrolyte additives (e.g., surfactants)
Low Energy Density	Limited application in high-performance sectors like EVs	Development of higher-capacity cathodes (e.g., hybrid, organic materials), improved electrolyte systems
Zinc Dissolution	Leads to capacity fading and poor cycle life	Optimized electrolytes, hybrid electrolytes, protective layers on anode
Cycle Stability	Degradation of cathode and anode materials over cycles	Composite cathodes, advanced separators, and better electrolyte formulations
Scalability for Commercialization	High manufacturing cost, inconsistent quality at scale	Standardization of manufacturing processes, cost-effective materials sourcing

REFERENCES

1. Y. Li, Z. H. Wang, Y. Cai, M. E. Pam, Y. K. Yang, D. H. Zhang, Y. Wang, S. Z. Huang, Energ. Environ. Mater. 2022, 5, 823.
2. Y. Ran, C. Xu, D. Ji, H. Zhao, L. Li, Y. Lei, Nano Research Energy 2024, 3, 9120092.
3. D. Yang, X. Y. Wu, L. He, H. N. Zhao, Y. Z. Wang, Z. Y. Zhang, J. Y. Qiu, X. B. Chen, Y. J. Wei, Nano Lett. 2023, 23, 11152.
4. C. F. Xu, J. J. Qiu, Y. L. Dong, Y. L. Li, Y. L. Shen, H. P. Zhao, U. Kaiser, G. S. Shao, Y. Lei, Energy Environ. Mater. 2024, 7, 12626.
5. C. Guo, S. J. Yi, R. Si, B. J. Xi, X. G. An, J. Liu, J. F. Li, S. L. Xiong, Adv. Energy Mater. 2022, 12, 2202039.
6. Y. Qiu, Z. Q. Yan, Z. H. Sun, Z. H. Guo, H. S. Liu, B. L. Du, S. Y. Tian, P. Wang, H. Ding, L. Qian, Inorganics 2023, 11, 118.
7. J. Kumankuma-Sarpong, W. Guo, Y. Z. Fu, Adv. Energ. Sust. Res. 2022, 3, 2100220.
8. M. J. Wu, G. X. Zhang, H. M. Yang, X. H. Liu, M. Dubois, M. A. Gauthier, S. H. Sun, Infomat 2022, 4, 12265.
9. U. Fegade, G. Jethave, F. Khan, A. Al-Ahmed, R. Karmouch, M. Shariq, M. F. A Inamuddin, Int. J. Energ. Res. 2022, 46, 13152.
10. Y. Q. Lv, Y. Xiao, L. T. Ma, C. Y. Zhi, S. M. Chen, Adv. Mater. 2022, 34, 2106409.
11. H. T. Xu, W. Y. Yang, M. Li, H. B. Liu, S. Q. Gong, F. Zhao, C. L. Li, J. J. Qi, H. H. Wang, W. C. Peng, J. P. Liu, Small

2024, 20, 2310972.

12. D. Bin, F. Wang, A. G. Tamirat, L. M. Suo, Y. G. Wang, C. S. Wang, Y. Y. Xia, Adv. Energy Mater. 2018, 8, 1703008.

13. Z. Y. Xing, S. Wang, A. P. Yu, Z. W. Chen, Nano Energy 2018, 50, 229.

14. J. Ren, Y. Ran, Z. C. Yang, H. P. Zhao, Y. D. Wang, Y. Lei, Small 2023, 19, 2303307.

15. F. L. Zhang, W. C. Zhang, D. Wexler, Z. P. Guo, Adv. Mater. 2022, 34, 2107965.

16. D. L. Chao, W. H. Zhou, F. X. Xie, C. Ye, H. Li, M. Jaroniec, S. Z. Qiao, Sci. Adv. 2020, 6, eaba4098.

17. J. H. Zhang, H. F. Zhang, Y. G. Zhang, X. M. Wang, H. F. Li, F. Feng, K. Wang, G. X. Zhang, S. H. Sun, Y. H. Zhang, J. Mater. Chem. A 2023, 11, 7924.

18. X. X. Jia, C. F. Liu, Z. G. Neale, J. H. Yang, G. Z. Cao, Chem. Rev. 2020, 120, 7795.

19. B. Wang, Y. Tang, T. Deng, J. Zhu, B. B. Sun, Y. Su, R. X. Ti, J. Y. Yang, W. J. Wu, N. Cheng, C. Y. Zhang, X. B. Lu, Y. Xu, J. F. Liang, Nanotechnology 2024, 35, 362004.

20. C. C. Kao, J. H. Liu, C. Ye, S. J. Zhang, J. N. Hao, S. Z. Qiao, J. Mater. Chem. A 2023, 11,

21. H. D. Zhang, X. T. Gan, Z. P. Song, J. P. Zhou, Angew. Chem., Int. Ed. 2023, 62, 202217833.

22. X. Zeng, Z. Gong, C. Wang, P. J. Cullen, Z. X. Pei, Adv. Energy Mater. 2024, 14, 2401704.

23. L. Ma, M. A. Schroeder, O. Borodin, T. P. Pollard, M. S. Ding, C. S. Wang, K. Xu, Nat. Energy 2020, 5, 743.

24. C. W. Li, Q. C. Zhang, E. Songfeng, T. T. Li, Z. Z. Zhu, B. He, Z. Y. Zhou, P. Man, Q. L. Li, Y. G. Yao, J. Mater. Chem. A 2019, 7, 2034.

25. Y. D. Hu, Z. X. Liu, L. Y. Li, S. Guo, X. F. Xie, Z. G. Luo, G. Z. Fang, S. Q. Liang, Natl. Sci. Rev. 2023, 10, nwad220.

26. Y. B. Yin, Z. Z. Yuan, X. F. Li, Phys. Chem. Chem. Phys. 2021, 23, 26070.

27. T. T. Wang, Y. Zhang, J. H. You, F. Hu, Chem. Rec. 2023, 23, 202200309.

28. X. W. Lv, Z. L. Wang, Z. Z. Lai, Y. P. Liu, T. Y. Ma, J. X. Geng, Z. Y. Yuan, Small 2024, 20, 2306396.

29. C. H. Nie, G. L. Wang, D. D. Wang, M. Y. Wang, X. R. Gao, Z. C. Bai, N. A. Wang, J. Yang, Z. Xing, S. X. Dou, Adv. Energy Mater. 2023, 13, 2300606.

30. M. Q. Zhu, X. R. Li, C. W. Shi, C. Y. Cai, J. D. Zhang, J. Energy Storage 2024, 101, 113686.

31. T. S. Zhang, Y. Tang, S. Guo, X. X. Cao, A. Q. Pan, G. Z. Fang, J. Zhou, S. Q. Liang, Energ. Environ. Sci. 2020, 13, 4625.

32. S. Guo, L. P. Qin, T. S. Zhang, M. Zhou, J. Zhou, G. Z. Fang, S. Q. Liang, Energy Storage Mater. 2021, 34, 545.

33. W. X. Wang, G. Huang, Y. Z. Wang, Z. Cao, L. Cavallo, M. N. Hedhili, H. N. Alshareef, Adv. Energy Mater. 2022, 12, 2102797.

34. X. D. Chen, J. H. Liu, H. X. Jiang, C. C. Zhan, Y. Gao, J. Y. Li, H. Zhang, X. H. Cao, S. X. Dou, Y. Xiao, Energy Storage Mater. 2024, 65, 103168.

35. X. M. Ma, X. X. Cao, M. L. Yao, L. T. Shan, X. D. Shi, G. Z. Fang, A. Q. Pan, B. A. Lu, J. Zhou, S. Q. Liang, Adv. Mater. 2022, 34, 2105452.

36. G. J. Li, L. Sun, S. L. Zhang, C. F. Zhang, H. Y. Jin, K. Davey, G. M. Liang, S. L. Liu, J. F. Mao, Z. P. Guo, Adv. Funct. Mater. 2024, 34, 2301291.

37. Z. Cai, Y. T. Ou, J. D. Wang, R. Xiao, L. Fu, Z. Yuan, R. M. Zhan, Y. M. Sun, Energy Storage Mater. 2020, 27, 205.

38. H. J. Tian, Z. Li, G. X. Feng, Z. Z. Yang, D. Fox, M. Y. Wang, H. Zhou, L. Zhai, A. Kushima, Y. G. Du, Z. X. Feng, X. N. Shan, Y. Yang, Nat. Commun. 2021, 12, 237.

39. N. Zhang, F. Y. Cheng, J. X. Liu, L. B. Wang, X. H. Long, X. S. Liu, F. J. Li, J. Chen, Nat. Commun. 2017, 8, 405.

40. H. S. Ao, W. D. Zhu, M. K. Liu, W. Q. Zhang, Z. G. Hou, X. J. Wu, Y. C. Zhu, Y. T. Qian, Small Methods 2021, 5, 2100418.