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$\text{Li}_{0.95}\text{Na}_{0.05}\text{FePO}_4$  as a trifunctional additive to boost the electrochemical performance of cathodes in lithium-sulfur batteries



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## Li<sub>0.95</sub>Na<sub>0.05</sub>FePO<sub>4</sub> as a trifunctional additive to boost the electrochemical performance of cathodes in lithium–sulfur batteries

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Lithium–sulfur batteries (LSBs) are regarded as some of the effective candidates for next-generation energy storage systems due to their high energy density. Conventional sulfur cathodes suffer from inadequate polysulfide adsorption and catalytic conversion capabilities, along with sluggish ion kinetics, leading to low utilization of active sulfur substances. These limitations hinder the practical application of LSBs. Here, micrometer-sized LNFP (Li<sub>0.95</sub>Na<sub>0.05</sub>FePO<sub>4</sub>) with enhanced ion conductivity is innovatively proposed as an additive for the cathode to address this challenge. Through theoretical analysis (density functional theory, DFT) and empirical experiments, it is found that Na<sup>+</sup> doping not only exposes effective adsorption sites but also alters the electronic environment of Fe<sup>2+</sup>/Fe<sup>3+</sup>, thereby enhancing the adsorption and catalytic conversion abilities of LFP towards polysulfides. The multifunctional LNFP additive contributes to high performance for S cathodes. As a result, the assembled LSB with the LNFP additive delivers an initial discharge specific capacity of 953 mAh g<sup>-1</sup> at 1 C and exhibits excellent cycling performance with a capacity decay of only 0.039% per cycle after 700 cycles. The prepared LSB retains a specific discharge capacity of 548 mAh g<sup>-1</sup> after 300 cycles at 5 C. The LSB demonstrates a discharge specific capacity of 880 mAh g<sup>-1</sup> under a high sulfur loading of 4.5 mg cm<sup>-2</sup>. This work opens up new avenues for optimizing the performance of LSBs.

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### Broader context

Lithium–sulfur batteries (LSBs) are regarded as leading candidates for next-generation energy-efficient vehicles due to their high theoretical energy density. However, conventional sulfur cathodes suffer from insufficient adsorption of polysulfide intermediates and poor catalytic conversion, leading to low utilization efficiency of active sulfur substances. Moreover, the thickness of sulfur cathodes can reach tens of micrometers, and the insulating nature of elemental sulfur hinders the effective movement of electrons and Li<sup>+</sup> ions. We initially propose micron-sized Li<sub>0.95</sub>Na<sub>0.05</sub>FePO<sub>4</sub> (LNFP), a Na<sup>+</sup>-doped LFP derivative with enhanced ionic conductivity, as a cathode additive to address these challenges. Our studies reveal that Na<sup>+</sup> doping effectively exposes more adsorption sites in LFP and enhances polysulfide adsorption *via* polythionate complex formation, with complete desorption achievable during redox cycling. Simultaneously, Na<sup>+</sup> doping alters the electronic environment of Fe<sup>2+</sup>/Fe<sup>3+</sup>, thereby boosting the inherent electronic conductivity of LFP. Consequently, this enables LNFP to convert adsorbed polysulfides into sulfides and S<sup>2-</sup> more effectively. Additionally, Na<sup>+</sup> doping widens ion migration channels for Li<sup>+</sup>, which leads to increased ionic conductivity. Benefiting from the aforementioned triple functions of LNFP, the assembled LSBs exhibit excellent cycling stability at 1 C, along with outstanding kinetic performance even under high sulfur loading and at high current density. This work provides novel insights into the design and fabrication of high-performance cathode additives, offering concrete guidance to facilitate the commercialization of advanced LSBs.

## Introduction

The vigorous development of the market is driving researchers to delve deep into the exploration of cutting-edge energy storage devices.<sup>1–5</sup> Among them, the research and development of secondary batteries with high capacity and a long life-span has become an unstoppable trend. With its exceptional high energy density (2600 Wh kg<sup>-1</sup>) and outstanding specific capacity (1675 mAh g<sup>-1</sup>), the lithium–sulfur battery (LSB) precisely aligns with the urgent demands of current market

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**Fig. 2** S 2p XPS spectra of (a) LFP-Li<sub>2</sub>S<sub>6</sub>, (b) LNFP-Li<sub>2</sub>S<sub>6</sub>, (c) C-S electrode, and (d) C-S-LNFP electrode (discharged to 1.8 V).

anchoring the polysulfides.<sup>39</sup> Besides, for the Li<sub>2</sub>S<sub>6</sub>-LNFP sample, a peak belonging to the intermediate product of the thiosulfate can also be detected at 166.7 eV. By combining theoretical calculations, we infer that LFP-based materials can bind with polysulfides to form polythionate complexes. Additionally, Na<sup>+</sup> doping widens the diffusion channels in LFP, providing more effective sites for adsorbing polysulfides, resulting in superior polysulfide adsorption of LNFP compared to LFP. After discharging the lithium-sulfur cells to 1.8 V, XPS tests were conducted on the C/S electrode and the C/S electrode doped with LNFP (Fig. 2c and d). Two consistent S 2p peaks are observed, indicating that the adsorbed sulfur substance can be completely desorbed from LNFP during the redox reaction process.

Cathodes doped with LFP and LNFP were prepared separately, and for comparison, an undoped cathode was also prepared. These cathodes are sequentially labeled as C-S-LFP, C-S-LNFP, and C-S. Subsequently, different cathodes are assembled into lithium-sulfur cells to evaluate the practical effects of various additives in applications. Different assembled cells were subjected to CV testing. The results indicate that the cell with the LNFP additive exhibits CV curves with a large peak area and narrow distance between oxidation and reduction peaks at 0.1 mV s<sup>-1</sup> (Fig. 3a). This characteristic suggests that the oxidation-reduction reactions in the C-S-LNFP/Li cells proceed fully, with weak polarization phenomena.<sup>40</sup> Besides, compared to the C-S/Li and C-S-LFP/Li cells, the C-S-LNFP/Li cells demonstrate excellent overlap in their first three CV curves (Fig. 3b and S12), strongly evidencing that LNFP can enhance the kinetic process of oxidation-reduction reactions.

At various scanning rates, the CV characteristics of different cells were tested. The observation results indicate that even when the scanning rate is increased to 0.5 mV s<sup>-1</sup>, the C-S-LNFP/Li cell still exhibits distinguishable oxidation-reduction peaks (Fig. 3c, S13a, and S13b). By utilizing linear



**Fig. 3** CV tests. (a) First-cycle CV curves of different cells at 0.1 mV s<sup>-1</sup>. (b) CV curves of the C-S-LNFP/Li cell at 0.1 mV s<sup>-1</sup>. (c) CV curves of the C-S-LNFP/Li cell at different scan rates and (d) the corresponding linear matching of peak point currents.

matching (Fig. 3d, S13c, and S13d), the Li<sup>+</sup> diffusion coefficients of different batteries under various voltage conditions were calculated. Upon comparative analysis, it is found that the Li<sup>+</sup> diffusion coefficient of the C-S-LNFP/Li cell is higher than that of the C-S/Li and C-S-LFP/Li cells (Table S1). This advantage is attributed to the enhanced ionic conductivity of LNFP, which facilitates the rapid migration of Li<sup>+</sup> cations.

After 100 cycles at 1 C, different lithium-sulfur cells were subjected to electrochemical impedance spectroscopy (EIS) tests (Fig. S14). Following these cycles, the C-S-LNFP/Li cell exhibits a reduced bulk resistance ( $R_s$ ) in comparison with both the C-S/Li and C-S-LFP/Li cells (Table S2). This indicates that LNFP as a cathode additive can provide more active reaction sites, which enhances the interaction between the electrolyte and sulfur. Notably, the interfacial resistance ( $R_{SEI}$ ) of the C-S-LNFP/Li cell is the lowest among the three, suggesting the formation of a more stable SEI (solid electrolyte interface) film during cycling.<sup>41</sup> This phenomenon can likely be attributed to the strong physical adsorption ability of LNFP for polysulfides, mitigating corrosion of the lithium anode. It is worth noting that the C-S-LNFP/Li cell also displays a low charge transfer resistance ( $R_{CT}$ ), an advantage that stems from the inherent excellent ionic conductivity of LNFP.<sup>42</sup> The low charge transfer resistance of the C-S-LNFP/Li cell also strongly demonstrates that Na doping enhances the intrinsic electronic conductivity of LFP.

At 1 C, the initial discharge specific capacities of C-S/Li, C-S-LFP/Li, and C-S-LNFP/Li cells are found to be 785 mAh g<sup>-1</sup>, 766 mAh g<sup>-1</sup>, and 953 mAh g<sup>-1</sup>, respectively (Fig. 4a). Among them, the C-S-LNFP cell exhibits a superior initial discharge specific capacity, surpassing the other two cells. This performance strongly demonstrates its efficient utilization of active sulfur substances. After 700 cycles, the capacity decay rates per cycle for these three cells are controlled at 0.084%, 0.059%, and a lower 0.039%, respectively. It is gratifying that the dis-





Fig. 4 The cycling performances of different cells at (a) 1 C and (b) 5 C.

charge specific capacity of the C-S-LNFP/Li cell still reaches 652 mAh g<sup>-1</sup> after prolonged cycling. The exceptional cycling performance of the C-S-LNFP/Li cell underscores the multiple roles of LNFP as a cathode additive: it not only suppresses the 'shuttle effect' but also enhances the kinetics of redox reactions. By analyzing the corresponding charge/discharge curves (Fig. S15), it can be observed that the discharge specific capacities of the C-S/Li and C-S-LFP/Li cells exhibit a relatively rapid decay trend. In contrast, the capacity of the C-S-LNFP/Li cell demonstrates remarkably stable retention. Compared to the other two cells, the C-S-LNFP/Li cell delivers superior specific discharge capacities across various current density conditions (Fig. S16). This performance strongly evidences that Na<sup>+</sup> doping in LFP can enhance the rate ability of the cathode. Furthermore, the C-S-LNFP/Li cell exhibits distinctly visible charge/discharge curves at different current densities, highlighting the notable advantages of LNFP in LSBs.<sup>43-45</sup> Compared to similar studies, this project demonstrates remarkable competitiveness (Table S3), convincingly showcasing the immense potential and value of LNFP as a high-performance sulfur cathode additive for commercial use.

The key challenge for the commercialization of LSBs lies in achieving good cycling stability under high sulfur loading and high current density conditions. Therefore, it is indispensable to conduct cycling performance tests on LSBs under such harsh conditions. At 5 C, the initial discharge specific capacities of C-S/Li, C-S-LFP/Li, and C-S-LNFP/Li cells are 384, 470, and 604 mAh g<sup>-1</sup>, respectively (Fig. 4b). Particularly noteworthy is that even under such demanding current density, the C-S-LNFP/Li cell can maintain a high discharge specific capacity, an achievement largely attributed to the excellent ion conductivity of LNFP itself. As expected, the C-S-LNFP/Li cell still retains a discharge specific capacity of 548 mAh g<sup>-1</sup> after 300 cycles at 5 C, and this remarkable cycling stability performance is likely due to the inherent high stability of LNFP. These results strongly demonstrate the superiority of Na<sup>+</sup> doping.

High sulfur loading cathodes were prepared, with the additive content maintained consistent with that in conventional sulfur loading cathodes. Subsequently, the assembled cells underwent cycling performance evaluations (Fig. S17). Unlike

the cathode without any additives, which exhibits low discharge specific capacities (only 320 mAh g<sup>-1</sup>), the cathode with added LNFP demonstrates higher discharge specific capacities (~880 mAh g<sup>-1</sup>) under high sulfur loading conditions (4.5 mg cm<sup>-2</sup>). This finding robustly confirms that even under harsh high sulfur loading conditions, LNFP can also promote the redox reaction kinetics within the battery, thereby highlighting its vast application prospects and tremendous potential as a commercial sulfur cathode additive. A lithium-sulfur pouch cell incorporating the LNFP additive in the cathode was fabricated to evaluate its electrochemical performance.<sup>46-48</sup> It shows a stable open circuit voltage of 2.96 V (Fig. S18a) and can power light emitting-diode lamps (Fig. S18b) showing the capital letters of blurred 'SEU'.

After 100 cycles at 1 C, the cells were disassembled in an argon-filled glove box, and the cathodes were subjected to SEM testing. For direct comparison, the cathodes before cycling were also tested using SEM. The observation results indicated that the cathodes before cycling all exhibit a loose and porous structure (Fig. 5a-c). However, the dense layers composed of deposited sulfur substances with lower electrochemical activity formed notably on the surfaces of the cycled C-S (Fig. 5d) and C-S-LFP (Fig. 5e) cathodes. The presence of these dense layers hinders the full utilization of active sulfur substances. In contrast, the cycled C-S-LNFP cathode retains a loose and porous structure (Fig. 5f) owing to the rapid ion transport channels enabled by LNFP, a feature that promotes deep polysulfide penetration and diffusion.<sup>49</sup> This result intuitively highlights the advantages of LNFP in the applications of LSBs.

With the aid of schematic illustrations, this paper visually demonstrates the notable advantages of LNFP in LSB applications. In the absence of any functional cathode additives (Fig. 6a), the prepared LSBs generate soluble polysulfides during operation, which can easily penetrate the separator, leading to irreversible loss of active materials and accelerated corrosion of the lithium anode. This phenomenon poses a serious threat to the service life and safety of LSBs, greatly hindering their commercialization process. In contrast, when



Fig. 5 SEM of cathodes: (a) C-S, (b) C-S-LFP, and (c) C-S-LNFP before cycling and (d-f) the corresponding cathodes after cycling (1 C, 100 cycles).





Fig. 6 Schematic diagrams of actions of the (a) C-S and (b) C-S-LNFP cathodes in LSBs (inset: partial enlargement).

LNFP is used as a functional additive for the cathode, its exceptional adsorption ability for sulfur substances anchors the generated polysulfides, preventing their unrestricted diffusion (Fig. 6b). Simultaneously, LNFP can accelerate the catalytic conversion of soluble polysulfides into insoluble sulfides, ensuring efficient utilization of active sulfur substances. The enhanced ionic conductivity of LNFP additionally ensures efficient ion transport, facilitating polysulfide diffusion within the cathode. The multifunctional effects of LNFP contribute to a high-performance sulfur cathode.

## Conclusions

In summary, micrometer-sized LNFP was successfully synthesized. We find that the prepared LNFP can effectively adsorb polysulfides due to the wide ion channels caused by  $\text{Na}^+$  doping. Additionally,  $\text{Na}^+$  doping alters the electronic environment of  $\text{Fe}^{2+}/\text{Fe}^{3+}$ , which improves the intrinsic electronic conductivity of LFP.  $\text{Na}^+$  doping also accelerates  $\text{Li}^+$  diffusion, leading to improved ionic transport kinetics. Through theoretical calculations and experimental verification, the practical feasibility of LNFP as a functional additive for the cathode of LSBs is confirmed. A LSB using LNFP as an additive exhibits a capacity decay rate of only 0.039% per cycle after 700 cycles at 1 C. Even at a high current density of 5 C, the assembled LSB can stably cycle 300 times while maintaining a discharge specific capacity of approximately  $600 \text{ mAh g}^{-1}$ . After cycling, no accumulation of non-conductive sulfur substances is observed on the surface of the cathode. This groundbreaking research addresses the current limitation of lithium salts as cathode additives with limited ionic conductivity and simultaneously broadens the selection scope of functional additive materials for cathodes, holding profound implications for the future commercialization of advanced LSBs.

## Experimental section

### Preparation of LFP and LNFP

The preparation of LNFP is similar to that in previous reports.<sup>33</sup> Briefly,  $\text{Na}_2\text{CO}_3$ ,  $\text{NH}_4\text{H}_2\text{PO}_4$ ,  $\text{FeC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ , and

$\text{Li}_2\text{CO}_3$  are meticulously measured and placed in an agate bowl based on their stoichiometric proportions. The ensuing mixture undergoes ball milling at a speed of 400 rpm for 10 hours. Subsequently, the mixture is subjected to a thermal treatment process under the protective atmosphere of argon. The heated product is subjected to ball milling once again to obtain the desired LNFP powder. LFP is prepared using the same method for comparison, except that  $\text{Na}_2\text{CO}_3$  is not added.

### Preparation of conventional sulfur loading cathodes

First, acidified carbon nanotubes (CNTs) and sublimed sulfur are mixed uniformly at a mass ratio of 3 : 7. Subsequently, this mixture is placed in a Teflon liner filled with argon gas. Then, the liner is placed inside a reaction kettle, which is then positioned within a muffle furnace ( $155^\circ\text{C}$ , 12 h). After the temperature in the muffle furnace naturally drops to room temperature, the reaction kettle is removed. Finally, the retrieved sample is ground, yielding a carbon-sulfur (C-S) composite material.

The C-S composite, PVDF (polyvinylidene difluoride), and conductive carbon, with a mass ratio of 8 : 1 : 1, are placed in a small beaker. An appropriate amount of NMP (*N*-methylpyrrolidone) is then added, and the mixture is magnetically stirred until a homogeneous slurry is formed. Subsequently, this slurry is poured onto the surface of aluminum foil and spread evenly. After undergoing vacuum drying overnight, the aluminum foil coated with the slurry is cut into small circular discs with a diameter of 10 mm, thus successfully obtaining the C-S cathodes. The preparation process for the C-S-LFP and C-S-LNFP cathodes is similar to that of the C-S cathode. In both cases, the content of LFP ( $\text{LiFePO}_4$ ) and LNFP in the cathode materials is controlled at 5 wt%. The sulfur loading is approximately  $1.0 \text{ mg cm}^{-2}$ .

### Preparation of high sulfur loading cathodes

High sulfur loading cathodes ( $4.5 \text{ mg cm}^{-2}$ ) are prepared according to the previous report.<sup>6</sup> The carbon-sulfur composite, CMC (carboxymethyl cellulose), and conductive carbon (the mass ratio is 7 : 1 : 1) are added to deionized water containing dissolved CMC. The mixture is stirred until forming a homogeneous slurry. This slurry is coated onto carbon-coated aluminum foil. Then, the aluminum foil loaded with different materials is vacuum-dried overnight and cut into small circular discs to obtain high-loading cathodes. The preparation of C-S-LFP and C-S-LNFP high sulfur loading cathodes follows the same procedure as that for the C-S cathode, except that LFP and LNFP are added to the slurry, respectively. The content of functional additives in the high sulfur loading cathodes is controlled to be the same as that in conventional sulfur loading cathodes.

### Assembly of coin-type cells

A sulfur cathode, a separator, and a lithium metal anode are sequentially encapsulated inside a CR2025 coin shell in an argon-filled glove box ( $\text{O}_2 < 0.1 \text{ ppm}$ ,  $\text{H}_2\text{O} < 0.1 \text{ ppm}$ ). After



being compacted under a certain pressure, a lithium–sulfur cell is obtained. The electrolyte (LS-009) is dripped onto both sides of the separator, with the electrolyte quantity precisely controlled for each cell (40  $\mu$ L). The prepared lithium–sulfur cells are labeled as C–S/Li, C–S-LFP/Li, and C–S-LNFP/Li cells, respectively, based on the different cathodes used.

As for testing the catalytic performance of LNFP towards polysulfides. The assembly process for the  $\text{Li}_2\text{S}_6$  symmetric cell is similar to that of the lithium–sulfur cell, with both the cathode and anode being the LNFP electrodes. The  $\text{Li}_2\text{S}_6$  electrolyte is dripped onto both sides of the separator. In addition, a pure LS-009 symmetric cell is prepared for comparison.

## Conflicts of interest

There are no conflicts of interest to declare.

## Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: <https://doi.org/10.1039/d5eb00160a>.

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## References

- Z. Fan, Y. Li, J. Pan, Z. Zhou, W. Li, T. Yang, H. Zhang, C. Shu, W. Hua, Y. Wu and W. Tang, *EES Batteries*, 2025, **1**, 100–118.
- C. Wu, Z. Wang, Z. Jia, J. Cui, C. Shu, X. Wang, Y. Wu and W. Tang, *EES Batteries*, 2025, **1**, 364–384.
- H. Liu, X. Liu, W. Li, X. Guo, Y. Wang, G. Wang and D. Zhao, *Adv. Energy Mater.*, 2017, **7**, 1700283.
- J. Guo, J. Huo, Y. Liu, W. Wu, Y. Wang, M. Wu, H. Liu and G. Wang, *Small Methods*, 2019, **3**, 1900159.
- S. Zheng, H. Geng, S. N. Eliseeva and B. Wang, *Energy Mater.*, 2022, **2**, 200042.
- S. Xia, Z. Lin, B. Peng, X. Yuan, J. Du, X. Yuan, L. L. Liu, L. J. Fu, R. Holze and Y. P. Wu, *Energy Environ. Sci.*, 2024, **17**, 5461.
- T. Wang, J. He, X.-B. Cheng, J. Zhu, B. Lu and Y. Wu, *ACS Energy Lett.*, 2022, **8**, 116–150.
- S. Xia, X. Xu, W. Wu, Y. Chen, L. Liu, G. Wang, L. Fu, Q. Zhang, T. Wang, J. He and Y. P. Wu, *Mater. Sci. Eng., R*, 2025, **163**, 100924.
- J. Song, S. Xia, N. Wang, J. Peng, B. Peng, W. Wu, L. Liu, X. Yuan, L. Fu, Y. Chen and Y. P. Wu, *Adv. Mater.*, 2024, **37**, 2418295.
- H. Song, K. Münch, X. Liu, K. Shen, R. Zhang, T. Weintraut, Y. Yusim, D. Jiang, X. Hong, J. Meng, Y. Liu, M. He, Y. Li, P. Henkel, T. Brezesinski, J. Janek and Q. Pang, *Nature*, 2025, **637**, 846–853.
- X. Pang, H. Geng, S. Dong, B. An, S. Zheng and B. Wang, *Small*, 2022, **19**, 2205525.
- J. Li, Z. Wang, K. Shi, Y. Wu, W. Huang, Y. Min, Q. Liu and Z. Liang, *Adv. Energy Mater.*, 2023, **14**, 2303546.
- Q. Chen, J. Li, J. Pan, T. Li, K. Wang, X. Li, K. Shi, Y. Min and Q. Liu, *Small*, 2024, **20**, 2401153.
- K. Li, T. Li, Z. Wang, K. Shi, Y. Sun, J. Li, J. Ren, A. Lu, X. Li and Q. Liu, *Adv. Funct. Mater.*, 2024, **34**, 2410517.
- Z. Wang, W. Huang, H. Wu, Y. Wu, K. Shi, J. Li, W. Zhang and Q. Liu, *Adv. Funct. Mater.*, 2024, **34**, 2409303.
- T. Li, K. Shi, X. Li, W. Huang, J. Li, J. Li, K. Wang, Y. Deng, H. Chen, Y. Min, J. Li and Q. Liu, *Adv. Funct. Mater.*, 2025, 2505615.
- X. Cui, X. Wang and Q. Pan, *Energy Mater.*, 2023, **3**, 300034.
- S. Shen, L. Huang, X. Tong, R. Zhou, Y. Zhong, Q. Xiong, L. Zhang, X. Wang, X. Xia and J. Tu, *Adv. Mater.*, 2021, **33**, 2102796.
- P. Han, S. H. Chung and A. Manthiram, *Small*, 2019, **15**, 1900690.
- Z. Luo, W. Lei, X. Wang, J. Pan, Y. Pan and S. Xia, *J. Alloys Compd.*, 2020, **812**, 152132.
- Z. Luo, X. Wang, W. Lei, P. Xia and Y. Pan, *J. Mater. Sci. Technol.*, 2020, **55**, 159–166.
- P. Zhu, J. Zhu, C. Yan, M. Dirican, J. Zang, H. Jia, Y. Li, Y. Kiyak, H. Tan and X. Zhang, *Adv. Mater. Interfaces*, 2018, **5**, 1701598.
- H. M. Kim, J.-Y. Hwang, S. Bang, H. Kim, M. H. Alfaruqi, J. Kim, C. S. Yoon and Y.-K. Sun, *ACS Energy Lett.*, 2020, **5**, 3168–3175.
- H.-E. Wang, K. Yin, N. Qin, X. Zhao, F.-J. Xia, Z.-Y. Hu, G. Guo, G. Cao and W. Zhang, *J. Mater. Chem. A*, 2019, **7**, 10346–10353.
- H. Lee, H. Nam and J. H. Moon, *Energy Storage Mater.*, 2024, **70**, 103551.
- N. Li, T. Meng, L. Ma, H. Zhang, J. Yao, M. Xu, C. M. Li and J. Jiang, *Nano-Micro Lett.*, 2020, **12**, 145.



- 27 K. Sun, M. Fu, Z. Xie, D. Su, H. Zhong, J. Bai, E. Dooryhee and H. Gan, *Electrochim. Acta*, 2018, **292**, 779–788.
- 28 M. Zheng, X. Gao, Y. Sun, K. Adair, M. Li, J. Liang, X. Li, J. Liang, S. Deng, X. Yang, Q. Sun, Y. Hu, Q. Xiao, R. Li and X. Sun, *Small Methods*, 2021, **5**, 2100176.
- 29 S. Xia, J. Song, Q. Zhou, L. L. Liu, J. L. Ye, T. Wang, Y. H. Chen, Y. K. Liu, Y. P. Wu and T. Ree, *Adv. Sci.*, 2023, **10**, 2301386.
- 30 S. Xia, Z. Chen, L. Yuan, J. Song, Q. Zhou, X. Yuan, L. Liu, L. Fu, Y. Chen and Y. Wu, *J. Mater. Chem. A*, 2023, **11**, 19870–19876.
- 31 X. Gao, C. Zheng, Y. Shao, V. R. Shah, S. Jin, J. Suntivich and Y. L. Joo, *ACS Appl. Mater. Interfaces*, 2023, **15**, 19011–19020.
- 32 S.-P. Chen, D. Lv, J. Chen, Y.-H. Zhang and F.-N. Shi, *Energy Fuels*, 2022, **36**, 1232–1251.
- 33 B. Peng, Z. Liu, Q. Zhou, X. Xiong, S. Xia, X. Yuan, F. Wang, K. I. Ozoemena, L. Liu, L. Fu and Y. P. Wu, *Adv. Mater.*, 2023, **36**, 2307142.
- 34 E. M. Lotfabad, J. Ding, K. Cui, A. Kohandehghan, W. P. Kalisvaart, M. Hazelton and D. Mitlin, *ACS Nano*, 2014, **8**, 7115–7129.
- 35 C. Barchasz, F. Molton, C. Duboc, J. C. Lepretre, S. Patoux and F. Alloin, *Anal. Chem.*, 2012, **84**, 3973–3980.
- 36 Q. Liang, S. Wang, X. Lu, X. Jia, J. Yang, F. Liang, Q. Xie, C. Yang, J. Qian, H. Song and R. Chen, *ACS Nano*, 2024, **18**, 2395–2408.
- 37 C. Shang, L. Cao, M. Yang, Z. Wang, M. Li, G. Zhou, X. Wang and Z. Lu, *Energy Storage Mater.*, 2019, **18**, 375–381.
- 38 J. Xu, S. An, X. Song, Y. Cao, N. Wang, X. Qiu, Y. Zhang, J. Chen, X. Duan, J. Huang, W. Li and Y. Wang, *Adv. Mater.*, 2021, **33**, 2105178.
- 39 X. Liang, C. Hart, Q. Pang, A. Garsuch, T. Weiss and L. F. Nazar, *Nat. Commun.*, 2015, **6**, 5682.
- 40 E. Jing, L. Chen, S. Xu, W. Tian, D. Zhang, N. Wang, Z. Bai, X. Zhou, S. Liu, D. Duan and X. Qiu, *J. Energy Chem.*, 2022, **64**, 574–582.
- 41 D. Yang, L. He, Y. Liu, W. Yan, S. Liang, Y. Zhu, L. Fu, Y. Chen and Y. Wu, *J. Mater. Chem. A*, 2019, **7**, 13679–13686.
- 42 A. Zhang, X. Fang, C. Shen, Y. Liu, I. G. Seo, Y. Ma, L. Chen, P. Cottingham and C. Zhou, *Nano Res.*, 2018, **11**, 3340–3352.
- 43 J. Zhou, C. Shu, J. Cui, C. Peng, Y. Liu, W. Hua, L. Simonelli, Y. Wu, S. X. Dou and W. Tang, *Carbon Energy*, 2024, **6**, e460.
- 44 Y. Ding, T. Yan, J. Wu, M. Tian, M. Lu, C. Xu, J. Gu, H. Zhao, Y. Wang, X. Pan, S. X. Dou, L. Zhang and J. Sun, *Appl. Catal., B*, 2024, **343**, 123553.
- 45 Q. Lv, Y. Sun, B. Li, C. Li, Q. Zhang and L. Wang, *Adv. Energy Mater.*, 2025, **15**, 2403223.
- 46 Y. Song, X. Long, Z. Luo, C. Guo, C.-N. Geng, Q.-S. Ouyang, Z. Han, G. Zhou and J.-J. Shao, *ACS Appl. Mater. Interfaces*, 2022, **14**, 32183–32195.
- 47 Y. Song, H. Li, J. Li, J. An, J.-J. Shao and G. Zhou, *J. Energy Chem.*, 2023, **87**, 51–60.
- 48 Y. Song, M. Zhou, Z. Chen, H. Nie, J.-J. Shao and G. Zhou, *Chin. Chem. Lett.*, 2024, **35**, 109200.
- 49 H. Yao, K. Yan, W. Li, G. Zheng, D. Kong, Z. W. Seh, V. K. Narasimhan, Z. Liang and Y. Cui, *Energy Environ. Sci.*, 2014, **7**, 3381–3390.

