Advances in Engineering Research : Possibilities and Challenges
ISSN Print: 3079-5192
ISSN Online: 3079-5206
https://doi.org/10.63313/AERpc.2008

Research progress on lithium dendrite growth

Yajing Guo
College of Material, Chemistry and Chemical Engineering, Key Laboratory of Organosilicon Chemistry and Material Technology, Min-istry of Education, Hangzhou Normal University, Hangzhou 311121 Zhejiang, PR China
Email: 2022111009021@stu.hznu.edu.cn

How to cite this paper: Guo, Y. J. (2025). Research progress on lithium dendrite growth. Advances in Engineering Research : Possibilities and Challenges, 1(1), 174–189. ISSN Print: 3079-5192. ISSN Online: 3079-5206.
https://doi.org/10.63313/AERpc.2008
Published: 2025-03-31

Abstract

This article reviews the progress in the growth mechanisms, suppression strate-gies, and monitoring techniques of lithium dendrites. The high - capacity poten-tial of lithium - metal anodes is restricted by cycle decay, short - circuits, and thermal runaway caused by dendrites. Their growth originates from elec-tro-chemical imbalance and interfacial heterogeneity. Multi - physics models re-veal the regulation rules of pore geometry and crystal orientation on morphology evolution. Suppression strategies center on constructing high - conductivity LiF interfaces, designing 3D porous anodes, and pressure control. In - situ charac-terization technologies (such as X - ray tomography and fiber - optic sens-ing) realize dynamic monitoring of the coupled mechanisms of dendrite growth and SEI reconstruction. Current challenges involve cross - scale model verification and real - time monitoring technology development. In the future, it's necessary to combine machine learning with intelligent sensor networks to promote the prac-tical application of high - safety lithium - metal batteries.

Keywords

Lithium dendrites; simulation model; in - situ characterization

1. Introduction

The vigorous progress of the new energy industry has propelled electrochemical energy storage technology to new heights. Lithium - ion batteries, with their re-markable specific energy, light weight, low self - discharge, and long cycle life, have become the core power source for mobile electronics and electric vehicles. However, the market's demand for battery energy density is growing much faster than the current technological improvements, thus demanding more from anode materials[4; 13; 48]. Although lithium - metal anodes have a high theoretical capacity (3860 mAh/g) and the lowest redox potential (-3.04 V vs. standard hydrogen electrode), their commercialization faces challenges like dendrite nucleation kinetics, lack of solid - liquid interface equilibrium, continuous irreversible active lithium loss, and electrode volume expansion, which hinder large - scale application[9; 30; 45; 56; 60; 66; 77].

2. Formation Mechanism of Lithium Dendrites

Lithium dendrites exhibit three dimensional morphologies including mossy, shrub and needle deposition patterns during cycling[36]. Barton et al. established a dendrite growth model based on diffusion dynamics for the first time, and proposed a theoretical hypothesis that spherical diffusion is better than linear diffusion to accelerate metal deposition on electrode surface protrusions[3]. The model assumes that the dendrite tip curvature radius has a negative correlation with the growth rate, but it is limited by the static hemispherical dendrite hypothesis and the linear simplification of electrochemical reaction kinetics, and does not include the effects of inertia force and mechanical stress. Subsequent scholars improved the model by gradually modifying the theoretical boundary conditions: Diggle et al. extended the applicability of the model by introducing dynamic dendrite morphology and high overpotential conditions[12]; Aogaki et al.(1981) revealed that topological instability induced by ion concentration gradient on electrode surface can aggravate the distortion of electrolyte concentration field[1]; Bruce et al.(1987) quantified the coupling effect of initial potential and ion concentration on electrode overpotential[6]. By the 1990s, the theoretical system was further integrated into multi-physical field coupling analysis. Chazalviel et al proposed that dendrite nucleation originated from electrochemical imbalance mechanism of space charge layer formation on electrode surface, but hydrodynamic factors were not considered[8]. Fleury et al.(1992) modified this theory by introducing electroconvection effect and established a dynamic growth model of equidistance linear dendrites and acicular dendrites during electrodeposition[15]. Brissot et al.(1999) combined in situ observation and electrochemical measurement to reveal for the first time the regulation law of current density on dendrite growth mode: ion depletion at anode interface triggers dendrite nucleation at high current density, while local interface heterogeneity dominates dendrite preferential growth at low current density[5]. Monroe et al. proved that dendrite tip growth rate is positively correlated with current density by curvature dependent kinetic model[46]. In recent years, focused micro-interface mechanism and defect engineering have been studied. The surface energy competition model proposed by Wang et al indicates that dendrite growth is induced by electrodeposition when the surface energy of substrate is lower than that of deposited film. Sun et al. demonstrated by in-situ microscopy that crystal defects in solid electrolytes (such as P/S-based defects in Li3PS4) can induce direct nucleation of lithium metal and initiate structural rupture of the electrolyte[55]. Further studies show that lithium ion flux distribution and active site density are significantly regulated by defect type and concentration of solid electrolyte, and defect regions become preferential nucleation sites due to faster deposition kinetics.

Upon contact with the electrolyte, lithium metal reacts instantly to form a solid electrolyte interphase (SEI) membrane composed of organic and inorganic substances. Ideally, a uniform SEI membrane can the electrode and prevent side reac-

tions. However, the actual SEI membrane often exhibits spatial chemical and mechanical property heterogeneity. Defective areas, due to charge concentration, create local high ion flux, causing lithium to deposit preferentially and form nanoscale protrusions. As cycling continues, the protrusion tips, under the electric field - strengthening effect, keep accumulating deposits until the original SEI membrane's mechanical strength threshold is exceeded. The exposed lithium metal then reacts with the electrolyte at the tips to generate a new SEI membrane, forming a dynamic interface. Yet, lithium deposition - induced volume expansion causes repeated SEI membrane rupture and regeneration, eventually allowing dendrites to penetrate the separator or solid - state electrolyte layer, triggering internal short circuits and thermal runaway in the battery[18; 28; 40; 53; 57; 64; 71].

3. Lithium Dendrite Simulation Model

3.1. Limitations of Traditional Two-Dimensional Models

Numerical simulation of lithium deposition in 3D porous electrode frameworks faces major methodological challenges. Traditional 2D modeling, due to dimensional reduction, struggles to accurately represent lithium - ion anisotropic transport in porous media. Specifically:

1. 2D models can't capture the topological constraints of 3D pore structures on ion diffusion paths, leading to significant prediction errors in local concentration and potential distributions.
2. The spatial charge shielding effects caused by complex 3D frameworks are underestimated in 2D approximations, reducing the reliability of studies on how charged framework surfaces regulate uniform lithium deposition[50].

3.2. 3D Multiphysics Field Coupling Model

Although Mu et al. enhanced 3D dendrite simulation efficiency with a parallel algorithm based on the AMReX framework, their model has two key flaws: the meso - structure reconstruction method for 3D porous electrodes lacks physical interpretability, and it fails to fully analyze the competitive growth kinetics between primary and secondary dendrites[47]. Similarly, Arguello et al. used the MOOSE platform with quadruple anisotropic solidification theory. While it successfully replicated 3D dendrite fractal growth, the model's over - reliance on empirical parameters limits its universality[2]. Moreover, it lacks a systematic explanation of the evolution mechanisms of non - fractal deposition modes like mossy and needle - like ones.

3.3. Model - Experimental Data Corroboration

To overcome multi - scale modeling technical bottlenecks, Qi's team developed a 3D electrochemical - thermodynamic - mechanical multiphysics - coupled phase - field model[50]. It first achieved comprehensive simulation of dendrite morphologies in porous electrode systems, including fractal dendrites, amorphous mossy bodies, uniaxial preferred needle crystals, and multi - level branched structures.

By introducing the synergistic mechanism of temperature gradient fields and crystal anisotropic tensors, the model quantitatively revealed two key laws: 1) The synergistic local supersaturation changes significantly affect ion migration barriers, shifting dendrite growth from fractal to amorphous. 2) The orientation - geometry matching error dominates the morphology selection.Despite successfully reproducing multi - modal dendrite growth, the model has theoretical gaps in the two - way coupling of SEI film dynamic reconstruction and volume stress, indicating future research directions for cross - scale modeling.

The model's predictive power is systematically verified by multi - dimensional experimental data. Using NDP - provided lithium deposition depth distribution data, Qi's model successfully calibrates the parameter of pore geometry matching in regulating dendrite growth[50]. Bruce's concentration - gradient model, via Aogaki's team's in - situ optical microscopy, quantifies the coefficient of ion concentration gradient at the electrode surface affecting electrolyte concentration field distortion.

These theoretical achievements offer key guidance for designing suppression strategies. The pore - geometry matching rule from Qi's model inspired Luo's team to create a 3D porous LiAl alloy anode. Its hierarchical pores reduce local current density, improving deposition uniformity. The curvature - dynamics parameter in Monroe's model sets a theoretical framework for pressure - regulation strategies, curbing dendrite - tip growth. These advances highlight multi - scale modeling's role in bridging basic research and engineering.

4. Lithium Dendrite Suppression Strategies

4.1. Electrolyte Engineering

The core strategy for suppressing lithium dendrite growth is optimizing the lithium/electrolyte interface stability and homogeneity. Electrolyte additives, being cost - effective and process - compatible, are the preferred choice for interfacial chemistry regulation. Introducing functional additives via molecular design can induce the formation of in - situ protective layers with high ionic conductivity and mechanical robustness, enhancing the initial SEI film's tolerance to volume expansion[31; 35; 61; 79]. Wang's team developed a methyl trifluoroacetate (MTFA) ether - based electrolyte additive system[62]. Its low - melting - point characteristic enables it to participate preferentially in the interfacial reduction reaction, generating inorganic SEI components rich in LiF. XPS depth profiling shows that this additive reduces H2O/HF residuals in the electrolyte and suppresses side reactions caused by over - charge/discharge through a chemical passivation effect.

4.2. Interface Regulation

The naturally formed SEI membrane, being intrinsically brittle, cannot withstand the drastic volume changes during lithium deposition/stripping[7; 24; 29; 42; 69]. To address this, Luo et al. introduced an interfacial engineering strategy for 3D porous

LiAl alloy anodes[44]. Through in - situ electrochemical dealloying and high - current - density pretreatment, they created a composite SEI layer with nano - Al2O3. This structure, with graded porosity and high specific surface area, reduces local current density, promotes uniform Li+ nucleation, and restrains dendrite growth. Synchrotron radiation micro - CT confirmed that this artificial interlayer, via stress - dissipation, delays SEI rupture, enhancing cycle life. Liu et al. developed a 3D honeycomb - like nitrogen - doped hierarchical framework. In - situ Raman spectroscopy revealed that nitrogen - containing functional groups direct Li+ adsorption for uniform nucleation, as evidenced by the decreasing defect - state density during cycling.

4.3. External Regulation

Monroe et al. proved via a curvature - dependent kinetic model that the growth rate of dendrite tips is positively related to current density. Recent research has focused on microscopic interfacial mechanisms and defect engineering[46].

5. Real - time Monitoring Methods for Lithium Dendrites

Uncontrolled lithium dendrite growth is the main cause of lithium - metal - battery - performance decline, leading to capacity decay, local heat accumulation, and internal hard short circuits. To understand the interrelations of these issues, real - time monitoring is urgently needed to track the dynamic changes in electrode material structure, SEI interface reconstruction, and dendrite morphology. For example, capacity decay is closely related to the dynamic changes in the SEI film's multi - phase composite structure, such as fluctuations in the organic - to - inorganic - component ratio, and the topological reconstruction of the electrode surface, like pore formation from lithium stripping.

Current research uses various characterization techniques to analyze the morphology and growth kinetics of lithium dendrites. However, traditional ex - situ methods, like SEM analysis after disassembling cycled batteries, have two main drawbacks. One is that they can only provide static structural information of the reaction - terminated state, failing to capture the staged growth of dendrites during charge/discharge. The other is that electrode exposure to air causes surface/interface passivation (e.g., oxidation of Li metal and hydrolysis of SEI components), leading to deviations from the true electrochemical state. To overcome these issues, researchers are shifting to in - situ characterization. Techniques like synchrotron - based X - ray tomography and in - situ AFM enable real - time analysis of dendrite growth pathways under actual battery conditions. They integrate time - resolution (millisecond - level) and space - resolution (nanometer - level) to dynamically track the distribution of local current density during Li deposition, the mechanical property evolution of the SEI film, and the 3D morphology evolution of dendrites, revealing their multi - scale correlation[14; 38].

5.1. X-ray characterization techniques

X - ray characterization techniques, with atomic - scale structural analysis and high

penetration, are crucial for probing lithium - metal - battery electrode reactions. In - situ X - ray diffraction (XRD), based on Bragg's law, enables non - invasive, real - time monitoring of electrode - material lattice - parameter changes and phase transitions during battery charge/discharge. Its combined millisecond - level temporal and nanometer - level spatial resolution advantages are widely used in studying solid - electrolyte crystal - structure evolution[73; 74]. For example, Cremasco et al. performed the first in - situ XRD study on a high - carbon - loading lithium - oxygen battery with a multi - walled carbon nanotube (MWCNT) - based electrode during full discharge/charge cycles[10]. The XRD results revealed the reaction kinetics of Br^-/Br_3^- in the high - carbon - loading electrode and confirmed that LiBr, acting as a redox mediator, helped solve catalytic issues, lower the charge - voltage plateau, and improve cyclability. Similarly, Lu et al. used in - situ XRD in 3D hierarchical lithium -philic matrices research to confirm that silver - nanoparticle - decorated nitrogen - doped carbon hollow structures can induce uniform lithium deposition, with diffraction - peak width changes indicating improved crystallinity of the deposited layer[43].

Unlike the bulk - structure sensitivity of XRD, X - ray photoelectron spectroscopy (XPS) can precisely analyze the chemical - state evolution and element depth distribution at the electrode/electrolyte interface by measuring photoelectron binding - energy shifts. This surface/interface - chemistry analysis capability makes XPS the preferred method for studying SEI - film dynamic reconstruction. Gao et al. used in - situ XPS to examine the interface between lithium metal and the Li1.5Al0.5Ge1.5(PO4)3 (LAGP) solid - state electrolyte, proving that a LiF - modified layer can prevent side reactions and suppress lithium - dendrite growth, while an Au - modified layer can reduce interfacial impedance and improve contact[16]. Huo et al. further confirmed via in - situ XPS that a thin polymer/thiophosphate composite interlayer can optimize Li+ flux distribution, with the continuous evolution of the interfacial phosphorus chemical state (P 2p spectrum) directly linked to enhanced dendrite - suppression efficiency[27]. However, XPS testing must be done in a high - vacuum environment, which imposes special requirements on battery packaging design and operating - condition simulation, restricting its universal application in fully liquid systems.

5.2. In Situ Raman Spectroscopy

Raman spectroscopy, with its fingerprint - like molecular vibration analysis, non - destructively reveals material crystallinity evolution, chemical bond changes, and phase - interface interactions, especially useful for amorphous and weakly crystalline materials compared to XRD. It provides in - situ diagnosis of lithium - metal - battery charge/discharge processes by tracking electrode/electrolyte - interface stress, structural relaxation, and dynamic chemical changes. However, its low sensitivity to non - polar bonds limits direct metallic - lithium observation, as signal strength depends on molecular vibration and rotation energy levels. Researchers

have expanded its application in dendrite - suppression - strategy evaluation by indirectly monitoring electrolyte and host - material structural responses[34; 76]. For example, Wu's team added LiAsF6 and fluorinated ethylene carbonate to commercial carbonate electrolytes[65]. LiAsF6 and FEC reduction forms LixAs and LiF, creating LiF - rich solid interfacial layers. In - situ Raman confirmed the synergetic effect of these additives in controlling lithium nucleation and growth. Similarly, Hu et al. used graphene - quantum - dot - modified electrolytes, with Raman peak shifts revealing dynamic double - layer structure modulation, offering spectroscopic evidence for dendrite suppression[25].

Further research focuses on the regulation of lithium - deposition behavior by electrode host - material design. Wu et al. introduced a dual additive of LiAsF6 and fluorinated ethylene carbonate, and in - situ Raman spectroscopy confirmed that it can suppress dendrite - preferred growth by regulating the solvation - sheath structure, offering a chemical - modification strategy for high - safety electrolyte design[65]. Liu et al. constructed a 3D honeycomb - like nitrogen - doped hierarchical framework. In - situ Raman spectroscopy tracked the defect - state - density decay during cycling, confirming that nitrogen - containing functional groups can direct uniform Li+ nucleation. Huang et al. designed a lithiophilic Ag - Cu mesh as a current collector to enhance rapid Li - ion flux and Li - metal nucleation[26]. They used dimethoxyethane (DME) and 1,3 - dioxolane (DOL) as co - solvents to lower interfacial resistance. In - situ Raman spectroscopy showed that bis (trifluoromethanesulfonyl) imide ($TFSI^-$) and DME molecules coordinate with Li+ more strongly than DOL molecules. These studies show that even though Raman spectroscopy cannot directly observe bulk metallic lithium, it can still indirectly reveal dendrite - growth - suppression mechanisms by correlating the structural responses of electrolyte components, interfacial chemistry, and host materials.

5.3. in Situ Resonance Spectroscopy

In - situ nuclear magnetic resonance (NMR) technology, with its high sensitivity to local nuclear chemical environments, enables non - destructive analysis of material electronic structure evolution and molecular dynamics. Its principle relies on nuclear spin energy level splitting in external magnetic fields. By detecting chemical shift changes caused by the electron cloud around the nucleus, it can qualitatively and quantitatively analyze the chemistry of electrode interfacial micro - areas. In lithium - metal - battery research, in - situ NMR is used to monitor the dynamic formation of lithium - deposition microstructures[49]. For example, Gunnarsdóttir et al. used in - situ 7Li NMR to compare inactive lithium amounts in LiFePO4||Cu full cells, showing that SEI formation significantly contributes to capacity loss in ether and ester electrolytes[20]. Gotoh et al. applied in - situ 7Li NMR to study over - lithiation of graphite and hard - carbon anodes in half - cells[19].

In - situ electron paramagnetic resonance (EPR) technology, which captures microwave absorption signals from unpaired electron transitions, offers higher spatial

resolution and sensitivity for radical detection and lithium microstructure analysis than NMR[52; 59]. Wandt's team pioneered an operational EPR method, using anisotropic g - factor changes to semi - quantitatively distinguish mossy and dendritic lithium deposits[58]. In Li's team's gradient SEI - modified porous copper current - collector system, the decay rate of characteristic peaks in in - situ EPR spectra correlates positively with cycle stability, confirming the kinetic advantage of dendrite - free deposition[37]. The introduction of EPR imaging (EPRI) enables 3D visualization of lithium - deposition morphology and local current density distribution, offering crucial experimental evidence for optimizing multi - scale dendrite - suppression strategies.

5.4. in Situ Microscopy

In - situ microscopy, offering dynamic visualization of lithium - dendrite morphology evolution and interfacial reactions, has become crucial for lithium - metal - battery research. Optical microscopy (OM), with its micrometer - level spatial resolution from light transmission and magnification, enables real - time imaging and has been adapted for lithium - metal - battery studies, tracking 3D dendrite evolution and interfacial reactions. For example, Hogrefe's team used cross - sectional in - situ OM to observe lithium - deposition topological reconstruction[23], and Liu's team designed a transparent cell with a Li6PS5Cl - PTFE composite electrolyte for the first in - situ optical tracking of dendrite growth in solid electrolytes. However, OM's utility is limited by the optical diffraction limit and sample transparency requirements, making it difficult to analyze nanoscale dendrite nucleation and internal structural changes in opaque electrodes[41].

Unlike OM’s macro - observation, SEM, via secondary - electron imaging in a vacuum, enables sub - micrometer - level surface - morphology analysis. Yadav et al. found varying surface roughness affects lithium deposition and crack - growth rates[70]. Dachraoui et al. used in - situ electrochemical liquid - cell scanning transmission electron microscopy to monitor in - real - time the cathode - electrolyte - interface nano - processes during Li - battery charge/discharge[11]. Note that SEM’s high - vacuum environment may introduce artifacts and miss electrolyte liquid - phase effects on deposition kinetics. TEM, leveraging elastic/inelastic scattering of high - energy electron beams with samples, enables atomic - scale analysis of lithium - deposition lattice reconstruction. Chi et al. first proved via in - situ TEM that LLZO electrolytes are where lithium dendrites originate[17]. Lee et al. used TEM imaging to study lithium - dendrite growth in batteries with sealed volatile liquid electrolytes[33].

In nanoscale interface analysis, atomic force microscopy (AFM), based on probe - surface interaction force detection, can non - destructively characterize the mechanical property evolution of electrode/electrolyte interfaces. Stępień et al. used AFM to study lithium nucleation in ionic liquid electrolytes, finding higher lithium - ion concentrations yield more uniform lithium deposits, and FEC addition signifi-

cantly alters lithium - metal nucleation morphology[54]. Yao et al. employed electrochemical AFM (EC - AFM) for in - depth study of SEI formation in LiFSI - 1,4 - dioxane electrolytes[72]. Zhang et al. used AFM to visualize Li - ion behavior at interfaces between different solid - state electrolytes, revealing Li - ion distribution at LGPS||LPS interfaces at various potentials[78]. Despite its sub - nanometer spatial resolution, AFM's slow scanning rate challenges the complete capture of rapid dynamic processes.

5.5. multi - modality characterization combined strategy

To comprehensively understand the multi - scale coupling in lithium - dendrite growth, researchers combine multiple in - situ characterization techniques, leveraging their spatial - temporal resolution strengths to overcome single - method limitations. For instance, Liu's team used in - situ AFM to track nanoscale lithium - anode morphology changes under additive control, supported by in - situ OM for cross - scale dendrite - morphology analysis[39]. Combined with in - situ Raman spectroscopy, they revealed the dynamic evolution of the Li2O||LiF ratio in the SEI membrane and the chemical - heterogeneity - induced dendrite nucleation. Similarly, Lu's team designed nitrogen - doped carbon hollow spheres with silver nanoparticles for a hetero -philic sulfur interface[43]. Using in - situ OM and XRD, they observed lithium - deposition morphology and crystal - orientation changes, confirming the dual control of interfacial chemistry modification on deposition uniformity.

The Zhang team integrated in - situ AFM and XPS to analyze the coupled mechanisms of SSE interfacial morphology evolution, chemical dynamics, and Li - ion deposition/stripping kinetics in Li - metal batteries[78]. They found that the Li||$Li_{10}GeP_2S_{12}$ (LGPS) system, a mixed ion - electron conductor, has a 40% faster Li - deposition rate than the pure ion - conductor Li||Li_3PS_4 (LPS) system, but similar SSE decomposition kinetics, with about 85% of the interfacial SSE components irreversibly converting to the SEI phase during cycling. Based on this, they designed an LPS - LGPS - LPS trilayer composite electrolyte, reducing the SSE decomposition rate to 25%. In - situ KPFM revealed that Li - ion distribution at the trilayer interface is potential - gradient - controlled, forming localized Li - ion - rich zones during charge/discharge, which effectively alleviates the space - charge - layer effect and offers crucial experimental support for high - stability interface design.

5.6. Embedded Sensor Technology

The demand for real - time and precise in - situ monitoring of lithium dendrites is driving the development of non - invasive battery sensors. Embedded sensor technology, with its in - situ non - destructive testing, high spatiotemporal resolution, and operational compatibility, offers a revolutionary solution for dynamically analyzing lithium - deposition behavior. Optical fiber sensors, resistant to electromagnetic interference and with multi - parameter sensing capabilities, show great potential in monitoring internal battery parameters[32]. Xi's team implanted short -

period fiber Bragg grating (FBG) into solid - state batteries to track lithium - dendrite - induced strain and temperature changes in real - time[67]. By correlating FBG reflection - wavelength shifts with dendrite - growth stress, they quantitatively determined the growth rate of lithium deposits, providing reliable data for battery - health assessment. This sensor network, preserving battery structural integrity, also lays the technical foundation for safety - early - warning systems in power batteries and energy - storage systems.

6. Challenges and Future Directions

6.1. Current Challenges

Understanding the dynamic mechanism of dendrite growth in lithium - metal batteries is crucial for designing high - safety, high - energy - density storage systems. During operation, the spatiotemporal heterogeneity of electrode - interfacial charge distribution causes non - uniform lithium - ion deposition, leading to uncontrolled lithium - metal - dendrite growth. This results in active - material loss, capacity decay, and safety hazards like internal short circuits and thermal runaway. Elucidating the multi - scale coupling of dendrite nucleation - growth - failure is vital for developing high - performance lithium - ion batteries[21; 22; 51; 63; 68; 75].

However, current research faces two main challenges. First, there's a big gap between the computational resources for cross - scale modeling and real - battery systems. Second, the chemical heterogeneity of the solid - electrolyte interphase (SEI) and continuous electrolyte decomposition complicate interfacial behavior, making traditional ex - situ characterization inadequate for capturing dendrite evolution. Thus, developing in - situ monitoring techniques to track dendrite growth in real - time under battery operating conditions is a key direction that needs urgent attention.

6.2. Future Directions

In the future, there is a need to develop multi - physics - coupled models with machine - learning - aided parameter optimization, combine EPRI imaging with sensor networks for dynamic condition monitoring, and design more self - healing materials and smart responsive interfaces to detect lithium - dendrite growth.

7. Conclusion

This review comprehensively examines recent advancements in lithium - dendrite - growth monitoring, focusing on in - situ characterization and sensor technologies. It compares the spatiotemporal resolution strengths and applicability boundaries of techniques like synchrotron - based X - ray tomography, in - situ AFM, and distributed fiber - optic sensing, highlighting their roles in understanding dendrite - growth kinetics. While significant progress has been made in nano - scale interface engineering and multi - modality in - situ observation, precise 3D - morphology analysis of dendrites throughout their life cycle remains technically challenging. Developing a real - time monitoring system with high spatiotemporal resolution and

operational compatibility is crucial for advancing our understanding of battery - failure mechanisms and guiding the design of safer batteries. This review offers methodological insights for accurately analyzing dendrite dynamics in metal - battery systems and combines multi - scale characterization with computational modeling to establish dendrite - suppression strategies.

Acknowledgements

The authors are grateful for the financial support of thePriority Academic Program Development of Zhejiang Higher Education Institutions.

References

[1] Aogaki, R., & Makino, T. (1981). Theory of powdered metal formation in electrochemistry—morphological instability in galvanostatic crystal growth under diffusion control. Electrochimica Acta, 26(11), 1509-1517. https://doi.org/https://doi.org/10.1016/0013-4686(81)85123-7

[2] Arguello, M. E., Labanda, N. A., Calo, V. M., Gumulya, M., Utikar, R., & Derksen, J. (2022). Dendrite formation in rechargeable lithium-metal batteries: Phase-field modeling using open-source finite element library. Journal of Energy Storage, 53. https://doi.org/10.1016/j.est.2022.104892

[3] Blomgren, G. E. (2017). The Development and Future of Lithium Ion Batteries. Journal of The Electrochemical Society, 164(1), A5019-A5025. https://doi.org/10.1149/2.0251701jes

[4] Brissot, C., Rosso, M., Chazalviel, J. N., & Lascaud, S. (1999). Dendritic growth mechanisms in lithium/polymer cells. Journal of Power Sources, 81-82, 925-929. https://doi.org/https://doi.org/10.1016/S0378-7753(98)00242-0

[5] Bruce, P. G., & Vincent, C. A. (1987). Steady state current flow in solid binary electrolyte cells. Journal of Electroanalytical Chemistry and Interfacial Electrochemistry, 225(1), 1-17. https://doi.org/https://doi.org/10.1016/0022-0728(87)80001-3

[6] Chang, S., Jin, X., He, Q., Liu, T., Fang, J., Shen, Z., . . . Lu, J. (2022). In Situ Formation of Polycyclic Aromatic Hydrocarbons as an Artificial Hybrid Layer for Lithium Metal Anodes. Nano Letters, 22(1), 263-270. https://doi.org/10.1021/acs.nanolett.1c03624

[7] Chazalviel, J. N. (1990). Electrochemical aspects of the generation of ramified metallic electrodeposits. Physical Review A, 42(12), 7355-7367. https://doi.org/10.1103/PhysRevA.42.7355

[8] Cheng, X., Zhang, R., Zhao, C., & Zhang, Q. (2017). Toward Safe Lithium Metal Anode in Rechargeable Batteries: A Review. Chemical Reviews, 117(15), 10403-10473. https://doi.org/10.1021/acs.chemrev.7b00115

[9] Cremasco, L. F., Anchieta, C. G., Nepel, T. C. M., Miranda, A. N., Sousa, B. P., Rodella, C. B., Doubek, G. (2021). Operando Synchrotron XRD of Bromide Mediated Li–O2 Battery. ACS Applied Materials & Interfaces, 13(11), 13123-13131. https://doi.org/10.1021/acsami.0c21791

[10] Dachraoui, W., Kühnel, R.-S., Battaglia, C., & Erni, R. (2024). Nucleation, growth and dissolution of Li metal dendrites and the formation of dead Li in Li-ion batteries investigated by operando electrochemical liquid cell scanning transmission electron microscopy. Nano Energy, 130. https://doi.org/10.1016/j.nanoen.2024.110086

[11] Diouf, B., & Pode, R. (2015). Potential of lithium-ion batteries in renewable energy. Renewable Energy, 76, 375-380. https://doi.org/10.1016/j.renene.2014.11.058

[12] Dutoit, C.-E., Tang, M., Gourier, D., Tarascon, J.-M., Vezin, H., & Salager, E. (2021). Monitoring metallic sub-micrometric lithium structures in Li-ion batteries by in situ electron paramagnetic resonance correlated spectroscopy and imaging. Nature Communications,

12(1). https://doi.org/10.1038/s41467-021-21598-2

[13] Fleury, V., Chazalviel, J. N., & Rosso, M. (1992). Theory and experimental evidence of electroconvection around electrochemical deposits. Physical Review Letters, 68(16), 2492-2495. https://doi.org/10.1103/PhysRevLett.68.2492

[14] Gao, A., Jiang, P., Duan, M., Lai, H., Zhou, Y., Zhang, X., . . . Meng, H. (2024). Interphase design enabling stable cycling of all-solid-state lithium metal batteries by in-situ X-ray photoelectron spectroscopy lithium metal sputtering. Journal of Power Sources, 602. https://doi.org/10.1016/j.jpowsour.2024.234299

[15] Gao, H., Ai, X., Wang, H., Li, W., Wei, P., Cheng, Y., . . . Wang, M.-S. (2022). Visualizing the failure of solid electrolyte under GPa-level interface stress induced by lithium eruption. Nature Communications, 13(1). https://doi.org/10.1038/s41467-022-32732-z

[16] Gao, Y., Du, X., Hou, Z., Shen, X., Mai, Y.-W., Tarascon, J.-M., & Zhang, B. (2021). Unraveling the mechanical origin of stable solid electrolyte interphase. Joule, 5(7), 1860-1872. https://doi.org/10.1016/j.joule.2021.05.015

[17] Gotoh, K., Yamakami, T., Nishimura, I., Kometani, H., Ando, H., Hashi, K., . . . Ishida, H. (2020). Mechanisms for overcharging of carbon electrodes in lithium-ion/sodium-ion batteries analysed by operando solid-state NMR. Journal of Materials Chemistry A, 8(29), 14472-14481. https://doi.org/10.1039/d0ta04005c

[18] Gunnarsdóttir, A. B., Amanchukwu, C. V., Menkin, S., & Grey, C. P. (2020). Noninvasive In Situ NMR Study of "Dead Lithium" Formation and Lithium Corrosion in Full-Cell Lithium Metal Batteries. Journal of the American Chemical Society, 142(49), 20814-20827. https://doi.org/10.1021/jacs.0c10258

[19] Guo, J., Li, Y., Pedersen, K., & Stroe, D.-I. (2021). Lithium-Ion Battery Operation, Degradation, and Aging Mechanism in Electric Vehicles: An Overview. Energies, 14(17), 5220. https://doi.org/10.3390/en14175220

[20] Guo, Y., Cai, J., Liao, Y., Hu, J., & Zhou, X. (2023). Insight into fast charging/discharging aging mechanism and degradation-safety analytics of 18650 lithium-ion batteries. Journal of Energy Storage, 72, 108331. https://doi.org/10.1016/j.est.2023.108331

[21] Hogrefe, C., Waldmann, T., Hölzle, M., & Wohlfahrt-Mehrens, M. (2023). Direct observation of internal short circuits by lithium dendrites in cross-sectional lithium-ion in situ full cells. Journal of Power Sources, 556. https://doi.org/10.1016/j.jpowsour.2022.232391

[22] Hou, C., Han, J., Liu, P., Yang, C., Huang, G., Fujita, T., . . . Chen, M. (2019). Operando Observations of SEI Film Evolution by Mass‐Sensitive Scanning Transmission Electron Microscopy. Advanced Energy Materials, 9(45), 1902675. https://doi.org/10.1002/aenm.201902675

[23] Hu, Y., Chen, W., Lei, T., Jiao, Y., Wang, H., Wang, X., . . . Xiong, J. (2020). Graphene quantum dots as the nucleation sites and interfacial regulator to suppress lithium dendrites for high-loading lithium-sulfur battery. Nano Energy, 68. https://doi.org/10.1016/j.nanoen.2019.104373

[24] Huang, D., Zeng, C., Liu, M., Chen, X., Li, Y., Zou, J., . . . Hu, S. (2025). In Operando Raman Spectroscopy Reveals Li‐Ion Solvation in Lithium Metal Batteries. Small, 21(10). https://doi.org/10.1002/smll.202412259

[25] Huo, H., Jiang, M., Mogwitz, B., Sann, J., Yusim, Y., Zuo, T. T., . . . Janek, J. (2023). Interface Design Enabling Stable Polymer/Thiophosphate Electrolyte Separators for Dendrite‐Free Lithium Metal Batteries. Angewandte Chemie International Edition, 62(14). https://doi.org/10.1002/anie.202218044

[26] Jana, A., Woo, S. I., Vikrant, K. S. N., & García, R. E. (2019). Electrochemomechanics of lithium dendrite growth. Energy & Environmental Science, 12(12), 3595-3607. https://doi.org/10.1039/C9EE01864F

[27] Jiang, G., Li, K., Yu, F., Li, X., Mao, J., Jiang, W., . . . Li, Y. (2021). Robust Artificial Solid‐Electrolyte Interfaces with Biomimetic Ionic Channels for Dendrite‐Free Li Metal Anodes. Advanced Energy Materials, 11(6), 2003496.

https://doi.org/10.1002/aenm.202003496

[28] Kang, J. H., Lee, J., Jung, J. W., Park, J., Jang, T., Kim, H. S., . . . Byon, H. R. (2020). Lithium Air Batteries: Air Breathing Challenges and Perspective. ACS Nano, 14(11), 14549-14578. https://doi.org/10.1021/acsnano.0c07907

[29] Kumar, R., Mitra, A., & Srinivas, T. (2022). Role of nano-additives in the thermal management of lithium-ion batteries: A review. Journal of Energy Storage, 48, 104059. https://doi.org/10.1016/j.est.2022.104059

[30] Lee, B. (2003). Review of the present status of optical fiber sensors. Optical Fiber Technology, 9(2), 57-79. https://doi.org/https://doi.org/10.1016/S1068-5200(02)00527-8

[31] Lee, S.-Y., Shangguan, J., Betzler, S., Harris, S. J., Doeff, M. M., & Zheng, H. (2022). Lithium metal stripping mechanisms revealed through electrochemical liquid cell electron microscopy. Nano Energy, 102. https://doi.org/10.1016/j.nanoen.2022.107641

[32] Li, H., Chao, D., Chen, B., Chen, X., Chuah, C., Tang, Y., . . . Qiao, S.-Z. (2020). Revealing Principles for Design of Lean-Electrolyte Lithium Metal Anode via In Situ Spectroscopy. Journal of the American Chemical Society, 142(4), 2012-2022. https://doi.org/10.1021/jacs.9b11774

[33] Li, J., Armstrong, B. L., Daniel, C., Kiggans, J., & Wood, D. L. (2013). Optimization of multicomponent aqueous suspensions of lithium iron phosphate (LiFePO4) nanoparticles and carbon black for lithium-ion battery cathodes. Journal of Colloid and Interface Science, 405, 118-124. https://doi.org/10.1016/j.jcis.2013.05.030

[34] Li, X., Zhang, Z., Fu, K., Yang, H., Wang, X., Yang, K., . . . Tan, P. (2023). Stress State Characterization of Li-Ion Batteries Based on a Membrane Sensor. Energy & Fuels, 37(17), 13526-13535. https://doi.org/10.1021/acs.energyfuels.3c02449

[35] Li, Z., Huang, X., Kong, L., Qin, N., Wang, Z., Yin, L., . . . Lu, Z. (2022). Gradient nano-recipes to guide lithium deposition in a tunable reservoir for anode-free batteries. Energy Storage Materials, 45, 40-47. https://doi.org/10.1016/j.ensm.2021.11.037

[36] Liu, D., Shadike, Z., Lin, R., Qian, K., Li, H., Li, K., . . . Li, B. (2019). Review of Recent Development of In Situ/Operando Characterization Techniques for Lithium Battery Research. Advanced Materials, 31(28). https://doi.org/10.1002/adma.201806620

[37] Liu, G. X., Wan, J., Shi, Y., Guo, H. J., Song, Y. X., Jiang, K. C., . . . Wan, L. J. (2022). Direct Tracking of Additive‐Regulated Evolution on the Lithium Anode in Quasi‐Solid‐State Lithium–Sulfur Batteries. Advanced Energy Materials, 12(40). https://doi.org/10.1002/aenm.202201411

[38] Liu, H., Cheng, X., Jin, Z., Zhang, R., Wang, G., Chen, L.-Q., . . . Zhang, Q. (2019). Recent advances in understanding dendrite growth on alkali metal anodes. EnergyChem, 1(1), 100003. https://doi.org/10.1016/j.enchem.2019.100003

[39] Liu, H., Jiang, W., Chen, W., Lin, Q., Ren, S., Su, Y., . . . Zhang, Y. (2024). Dendrite growth and inhibition in all-solid-state lithium metal batteries: in situ optical observation. Journal of Materials Chemistry A, 12(6), 3575-3579. https://doi.org/10.1039/d3ta07366a

[40] Liu, W., Liu, P., & Mitlin, D. (2020). Review of Emerging Concepts in SEI Analysis and Artificial SEI Membranes for Lithium, Sodium, and Potassium Metal Battery Anodes. Advanced Energy Materials, 10(43), 2002297. https://doi.org/10.1002/aenm.202002297

[41] Lu, X. M., Liu, T., Wang, Y., & Du, F. H. (2022). Inside‐Outside Lithium Deposition Achieved by the Unusual Strategy of Constructing the Hierarchical Lithiophilicity for Dendrite‐Free and Durable Lithium Metal Anode. Batteries & Supercaps, 5(8). https://doi.org/10.1002/batt.202200114

[42] Luo, B., Wang, Q., Ji, W., Yu, G., Zhao, Z., Zhao, R., . . . Zhang, J. (2024). Suppressing lithium dendrite via hybrid interface layers for high performance quasi-solid-state lithium metal batteries. Chemical Engineering Journal, 492, 152152. https://doi.org/10.1016/j.cej.2024.152152

[43] Lyu, T., Luo, F., Wang, D., Bu, L., Tao, L., & Zheng, Z. (2022). Carbon/Lithium Composite Anode for Advanced Lithium Metal Batteries: Design, Progress, In Situ Characterization,

and Perspectives. Advanced Energy Materials, 12(36), 2201493. https://doi.org/10.1002/aenm.202201493

[44] Mu, Z., Guo, Z., & Lin, Y.-H. (2020). Simulation of 3-D lithium dendritic evolution under multiple electrochemical states: A parallel phase field approach. Energy Storage Materials, 30, 52-58. https://doi.org/10.1016/j.ensm.2020.04.011

[45] Nayak, P. K., Yang, L., Brehm, W., & Adelhelm, P. (2018). From Lithium - Ion to Sodium - Ion Batteries: Advantages, Challenges, and Surprises. Angewandte Chemie International Edition, 57(1), 102-120. https://doi.org/10.1002/anie.201703772

[46] Pecher, O., Carretero-González, J., Griffith, K. J., & Grey, C. P. (2016). Materials' Methods: NMR in Battery Research. Chemistry of Materials, 29(1), 213-242. https://doi.org/10.1021/acs.chemmater.6b03183

[47] Qi, G., Liu, X., Dou, R., Wen, Z., Zhou, W., & Liu, L. (2024). A three-dimensional multiphysics field coupled phase field model for lithium dendrite growth. Journal of Energy Storage, 101. https://doi.org/10.1016/j.est.2024.113899

[48] Rahman, T., & Alharbi, T. (2024). Exploring Lithium-Ion Battery Degradation: A Concise Review of Critical Factors, Impacts, Data-Driven Degradation Estimation Techniques, and Sustainable Directions for Energy Storage Systems. Batteries, 10(7), 220. https://doi.org/10.3390/batteries10070220

[49] Sathiya, M., Leriche, J. B., Salager, E., Gourier, D., Tarascon, J. M., & Vezin, H. (2015). Electron paramagnetic resonance imaging for real-time monitoring of Li-ion batteries. Nature Communications, 6(1). https://doi.org/10.1038/ncomms7276

[50] Shen, X., Zhang, R., Chen, X., Cheng, X. B., Li, X., & Zhang, Q. (2020). The Failure of Solid Electrolyte Interphase on Li Metal Anode: Structural Uniformity or Mechanical Strength? Advanced Energy Materials, 10(10), 1903645. https://doi.org/10.1002/aenm.201903645

[51] Stępień, D., Wolff, B., Diemant, T., Kim, G.-T., Hausen, F., Bresser, D., & Passerini, S. (2023). Insights into the Lithium Nucleation and Plating/Stripping Behavior in Ionic Liquid-Based Electrolytes. ACS Applied Materials & Interfaces, 15(21), 25462-25472. https://doi.org/10.1021/acsami.3c01722

[52] Sun, M., Liu, T., Yuan, Y., Ling, M., Xu, N., Liu, Y., . . . Lu, J. (2021). Visualizing Lithium Dendrite Formation within Solid-State Electrolytes. ACS Energy Letters, 6(2), 451-458. https://doi.org/10.1021/acsenergylett.0c02314

[53] Tao, T., Lu, S., Fan, Y., Lei, W., Huang, S., & Chen, Y. (2017). Anode Improvement in Rechargeable Lithium–Sulfur Batteries. Advanced Materials, 29(48), 1700542. https://doi.org/10.1002/adma.201700542

[54] Tung, S., Ho, S., Yang, M., Zhang, R., & Kotov, N. A. (2015). A dendrite-suppressing composite ion conductor from aramid nanofibres. Nature Communications, 6(1), 6152. https://doi.org/10.1038/ncomms7152

[55] Wandt, J., Marino, C., Gasteiger, H. A., Jakes, P., Eichel, R.-A., & Granwehr, J. (2015). Operando electron paramagnetic resonance spectroscopy – formation of mossy lithium on lithium anodes during charge–discharge cycling. Energy & Environmental Science, 8(4), 1358-1367. https://doi.org/10.1039/c4ee02730b

[56] Wang, B., Wang, W., Sun, K., Xu, Y., Sun, Y., Li, Q., . . . Wu, M. (2023). Developing in situ electron paramagnetic resonance characterization for understanding electron transfer of rechargeable batteries. Nano Research, 16(10), 11992-12012. https://doi.org/10.1007/s12274-023-5855-z

[57] Wang, D., Zhang, W., Zheng, W., Cui, X., Rojo, T., & Zhang, Q. (2017). Towards High - Safe Lithium Metal Anodes: Suppressing Lithium Dendrites via Tuning Surface Energy. Advanced Science, 4(1), 1600168. https://doi.org/10.1002/advs.201600168

[58] Wang, G., Xiong, X., Xie, D., Fu, X., Ma, X., Li, Y., . . . Liu, M. (2019). Suppressing dendrite growth by a functional electrolyte additive for robust Li metal anodes. Energy Storage Materials, 23, 701-706. https://doi.org/10.1016/j.ensm.2019.02.026

[59] Wang, Y., Ren, L., Zhang, Q., Pato, A. H., Liu, J., Lu, X., & Liu, W. (2024). Fluorine-Rich

Electrolyte Additive for Achieving Dendrite-Free Lithium Anodes at Low Temperatures. ACS Applied Materials & Interfaces, 16(36), 47674-47682. https://doi.org/10.1021/acsami.4c10028

[60] Wang, Z., Liu, J., Wang, M., Shen, X., Qian, T., & Yan, C. (2020). Toward safer solid-state lithium metal batteries: a review. Nanoscale Advances, 2(5), 1828-1836. https://doi.org/10.1039/D0NA00174K

[61] Wei, C., Tan, L., Tao, Y., An, Y., Tian, Y., Jiang, H., . . . Qian, Y. (2021). Interfacial passivation by room-temperature liquid metal enabling stable 5 V-class lithium-metal batteries in commercial carbonate-based electrolyte. Energy Storage Materials, 34, 12-21. https://doi.org/10.1016/j.ensm.2020.09.006

[62] Wu, B., Chen, C., Danilov, D. L., Chen, Z., Jiang, M., Eichel, R. A., & Notten, P. H. L. (2023). Dual Additives for Stabilizing Li Deposition and SEI Formation in Anode‐Free Li‐Metal Batteries. ENERGY & ENVIRONMENTAL MATERIALS, 7(3). https://doi.org/10.1002/eem2.12642

[63] Wu, F., Yuan, Y., Cheng, X., Bai, Y., Li, Y., Wu, C., & Zhang, Q. (2018). Perspectives for restraining harsh lithium dendrite growth: Towards robust lithium metal anodes. Energy Storage Materials, 15, 148-170. https://doi.org/10.1016/j.ensm.2018.03.024

[64] Xi, J., Li, J., Sun, H., Ma, T., Deng, L., Liu, N., . . . Zhang, J. (2022). In-situ monitoring of internal temperature and strain of solid-state battery based on optical fiber sensors. Sensors and Actuators A: Physical, 347. https://doi.org/10.1016/j.sna.2022.113888

[65] Xiao, J. (2019). How lithium dendrites form in liquid batteries. Science, 366(6464), 426-427. https://doi.org/10.1126/science.aay8672

[66] Xu, R., Zhang, X. Q., Cheng, X. B., Peng, H. J., Zhao, C. Z., Yan, C., & Huang, J. Q. (2018). Artificial Soft‐Rigid Protective Layer for Dendrite‐Free Lithium Metal Anode. Advanced Functional Materials, 28(8), 1705838. https://doi.org/10.1002/adfm.201705838

Yadav, N. G., Folastre, N., Bolmont, M., Jamali, A., Morcrette, M., & Davoisne, C. (2022). Study of failure modes in two sulphide-based solid electrolyte all-solid-state batteries via in situ SEM. Journal of Materials Chemistry A, 10(33), 17142-17155. https://doi.org/10.1039/d2ta01889f

[67] Yamaki, J., Tobishima, S., Hayashi, K., Keiichi, S., Nemoto, Y., & Arakawa, M. (1998). A consideration of the morphology of electrochemically deposited lithium in an organic electrolyte. Journal of Power Sources, 74(2), 219-227. https://doi.org/10.1016/S0378-7753(98)00067-6

[68] Yao, Y.-X., Wan, J., Liang, N.-Y., Yan, C., Wen, R., & Zhang, Q. (2023). Nucleation and Growth Mode of Solid Electrolyte Interphase in Li-Ion Batteries. Journal of the American Chemical Society, 145(14), 8001-8006. https://doi.org/10.1021/jacs.2c13878

[69] Zhang, G., Xiong, T., He, L., Yan, M., Zhao, K., Xu, X., & Mai, L. (2017). Electrochemical in situ X-ray probing in lithium-ion and sodium-ion batteries. Journal of Materials Science, 52(7), 3697-3718. https://doi.org/10.1007/s10853-016-0732-8

[70] Zhang, L., Fan, H., Dang, Y., Zhuang, Q., Arandiyan, H., Wang, Y., . . . Liu, Y. (2023). Recent advances in in situ and operando characterization techniques for Li7La3Zr2O12-based solid-state lithium batteries. Materials Horizons, 10(5), 1479-1538. https://doi.org/10.1039/d3mh00135k

[71] Zhang, L., Yu, H., Wang, W., Xie, H., Wang, M., Yang, S., . . . Liu, X. (2022). Revealing the lithium dendrite deposition/dissolution progression based on Monte Carlo method. Journal of Energy Storage, 55, 105473. https://doi.org/10.1016/j.est.2022.105473

[72] Zhang, R., Wu, Y., Chen, Z., Wang, Y., Zhu, J., & Zhuang, X. (2023). The value of in situ/operando Raman spectroscopy in all-solid-state Li batteries. Journal of Materials Chemistry A, 11(36), 19195-19209. https://doi.org/10.1039/d3ta03514j

[73] Zhang, X., Wang, A., Liu, X., & Luo, J. (2019). Dendrites in Lithium Metal Anodes: Suppression, Regulation, and Elimination. Accounts of Chemical Research, 52(11), 3223-3232. https://doi.org/10.1021/acs.accounts.9b00437

[74] Zhang, X. S., Wan, J., Shen, Z. Z., Lang, S. Y., Xin, S., Wen, R., . . . Wan, L. J. (2024). In Situ

Analysis of Interfacial Morphological and Chemical Evolution in All‐Solid‐State Lithium‐Metal Batteries. Angewandte Chemie International Edition, 63(38). https://doi.org/10.1002/anie.202409435

[75] Zhu, Y., Ge, M., Ma, F., Wang, Q., Huang, P., & Lai, C. (2024). Multifunctional Electrolyte Additives for Better Metal Batteries. Advanced Functional Materials, 34(5), 2301964. https://doi.org/10.1002/adfm.202301964