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Challenges and strategies for aluminum-air batteries

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Aluminum-air (Al-air) batteries are considered promising candidates for electrochemical energy storage due to their theoretical energy density (~8,100 Wh kg^{-1}), specific capacity (~3000 mAh·g^{-1}), low cost and the natural abundance of aluminum. However, several hurdles must be overcome before their widespread application. Notably, the aluminum anode is prone to passivation and corrosion, which reduces the effective utilization of the metal. In addition, the sluggish oxygen reduction reaction (ORR) affects the air cathode and significantly decreases the electrochemical performance of the system. These problems are mitigated with different strategies: the aluminum anode is usually coated with other metal elements to improve the battery performance. On the other hand, different materials have emerged to improve the oxygen reduction reaction activity in the air cathode, such as metal-organic frameworks (MOFs). In this mini-review, the challenges and recent advances in aluminum-air technology are examined, highlighting the use of metal-organic frameworks as catalysts for the air cathode and the application of different coating strategies to improve the stability and performance of the aluminum anode.

KEYWORDS
aluminum-air batteries, anode coating, corrosion, metal-organic frameworks, oxygen reduction reaction

1 Introduction

The transition toward renewable energy systems has highlighted the need for efficient ways to store energy. Electrochemical energy storage systems have emerged as a link between energy demand and supply (Liu et al., 2010). Currently, lithium-ion batteries (LIBs) dominate the market due to their energy density (150–250 Wh kg^{-1}); however, a lifespan of 1000–1500 cycles remains a limitation (Wang et al., 2022). Nevertheless, concerns regarding lithium availability and environmental impact have driven the search for alternatives (Kim et al., 2019). In this context, systems based on sodium (Na) (Yabuuchi et al., 2014), potassium (K) (He et al., 2024), magnesium (Mg) (Aurbach et al., 2000) and aluminum (Al) (Elia et al., 2016; Elia et al., 2017) are considered next-generation energy storage systems. Among these, aluminum (Al)-based batteries have attracted interest owing to their benefits, including low cost and long cycle life (hundreds to over 10, 000 cycles) (Das et al., 2017).

Aluminum-battery technology is divided into: (i) aluminum–air (Al-air) batteries, (ii) aluminum-ion (Al-ion) batteries, and (iii) aluminum–sulfur (Al-S) batteries. Of these, aluminum–air batteries are particularly notable for their theoretical energy density (~8,100 Wh kg^{-1}), and specific capacity (~3000 mAh·g^{-1}) (Nandi and Pumera, 2025).

As illustrated in Figure 1a, an Al-air battery (AAB) comprises an aluminum anode (Al-anode), a porous air cathode, an alkaline electrolyte, and a separator. The air cathode is typically a composite structure that includes a gas diffusion layer (GDL) to manage gas

transport while preventing electrolyte leakage, alongside a current collector to ensure electron transfer to the external circuit. The electrolyte, typically alkaline, acts as ionic conductor (Nandi and Pumera, 2025). The separator physically isolates the electrodes, while still permitting the passage of ions (Shah, 2021; Liu et al., 2020).

At the cathode side (Figure 1b), atmospheric oxygen diffuses into the porous cathode, reaching the triple-phase boundary (TPB) (Elia et al., 2016; Li and Dai, 2014; Han et al., 2023). The efficiency of the battery is dictated by the ORR pathway. The ideal route is the direct four-electron pathway (Equation 1) (Han et al., 2023):

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (1)$$

Alternatively, a kinetically sluggish two-electron pathway may take place, leading to the formation of peroxide intermediates (Equation 2):

$$O_2 + 2H_2O + 2e^- \rightarrow HO_2^- + OH^- \quad (2)$$

Simultaneously, during discharge, hydroxide ions migrate through the electrolyte toward the anode, where Al is oxidized and forms aluminum hydroxide, Al $(OH)_3$ (Nandi and Pumera, 2025; Du et al., 2024), releasing electrons to the external circuit (Equation 3) (Du et al., 2024; Liu et al., 2024):

$$Al + 3OH^- \rightarrow Al(OH)_3(s) + 3e^- \quad (3)$$

Nevertheless, the accumulation of $Al(OH)_3$(s) in the anode surface becomes a detrimental physical barrier, how is shown in Figure 1c. Passivation layer hinders the continuous diffusion of hydroxide ions to the active aluminum surface and blocks further electron transfer, ultimately impeding the electrochemical reaction and degrading battery performance.

Therefore, the development of efficient electrocatalysts and protective strategies for the aluminum anode is essential. This mini-review summarizes recent advances in Al–air batteries (AABs), focusing on MOFs for air cathodes and coating strategies for anodes to improve performance and stability.

2 Background

This section focuses on strategies for solving both problems: (i) MOFs as catalysts for ORR activity at cathode (Figure 2a), and (ii) protective coatings to mitigate aluminum corrosion (Figure 2b) and self-passivation.

2.1 Metal-organic frameworks (MOFs) as cathode catalysts

MOFs have emerged as promising ORR catalysts in the air cathode due to their high surface area, and hierarchical porosity, which optimize the TPB, facilitating oxygen diffusion and electrolyte ion transport (Lu and Su, 2025). Also, MOFs-derived materials modulate the Gibbs free energy (Δ G) of oxygenated intermediates (Dhanabalan et al., 2023) optimizing adsorption/desorption steps and favoring the four-electron pathway (Lu and Su, 2025; Yang et al., 2022). MOFs typically exhibit half-wave potentials (E1/2) of ~0.80–0.90 V vs. RHE (Reversible Hydrogen Electrode) and electron transfer numbers (n ≈ 4.0, where n is the number of electrons transferred per O_2 molecule), indicating efficient ORR kinetics comparable to Pt/C (Platinum supported on conductive carbon) catalysts. Recent studies focus on MOF-derived materials, including carbon materials (Li et al., 2020), single doped-carbon materials (Chen et al., 2019) and bimetallic doped-carbon materials (Xiao et al., 2020), which exhibit improved electrical conductivity and catalytic performance (Lu and Su, 2025).

2.1.1 MOF-derived carbon materials

MOFs are synthesized through hydrothermal methods, where metal ions (e.g., Fe) are coordinated with organic ligands to form porous crystalline structures. Despite MOFs having a high density of active sites (Li et al., 2020), their intrinsically low electrical conductivity limits direct application in electrocatalysis. This limitation is overcome by using pyrolysis to transform the organic ligands into a conductive graphitic carbon while preserving the topological features and dispersing metal or metal-compound nanoparticles. Li et al (2020) fabricated a uniform FeS/Fe_3C nanoparticles embedded in a porous N, S-dual doped carbon honeycomb-like composite by pyrolysis of a single-crystal Fe-MOF. The catalyst exhibited a four-electron dominant ORR pathway, indicating efficient oxygen reduction kinetics. In addition, its durability (≥6 h stability in alkaline media) suggests that the N, S-doped carbon matrix stabilizes the active sites and suppresses metal aggregation. Compared to commercial catalysts Pt/C catalyst, this behavior indicates comparable catalytic activity with enhanced long-term stability, which is critical for practical Al–air battery operation.

2.1.2 Single-metal doped carbon catalysts

Single-metal doped carbon catalysts have surfaced as promising non-precious electrocatalyst materials for ORR (Chen et al., 2019), specifically those with Fe sites embedded in N-doped carbon matrices. These catalysts combine a high density of isolated Fe–N_x active centers with hierarchical porosity obtained from MOFs, thereby improving mass transport and increasing the available active surface area. Chen et al. (2019) developed a melamine-assisted co-calcination of Fe-ZIF-8, producing Fe@NMC-1 with Fe–N_x active sites, 3D hierarchical porosity, and high surface area. This structure exhibit performance comparable or superior to commercial Pt/C, typically showing half-wave potentials ($E_{1/2}$) close to ~0.85 V vs. RHE and electron transfer numbers approaching 4.0. This behavior is attributed to the concentration of Fe–N_x active sites, which enhance the adsorption energy of oxygen intermediates and facilitates the four-electron reduction pathway.

2.1.3 Bimetallic-doped carbon catalysts

Bimetallic-doped carbon catalysts have garnered interest as ORR electrocatalysts due to the synergistic effect between different metal centers. The addition of two metals alters the electronic configuration of active sites, improving catalytic activity and catalyst stability (Macedo et al., 2021). Xiao et al. (2020) synthetized a bimetallic ZnCo-ZIF@graphene oxide (ZnCo-ZIF@GO) hybrid electrocatalyst prepared through the in-situ growth of ZnCo-ZIF (zeolitic imidazolate frameworks) on graphene oxide

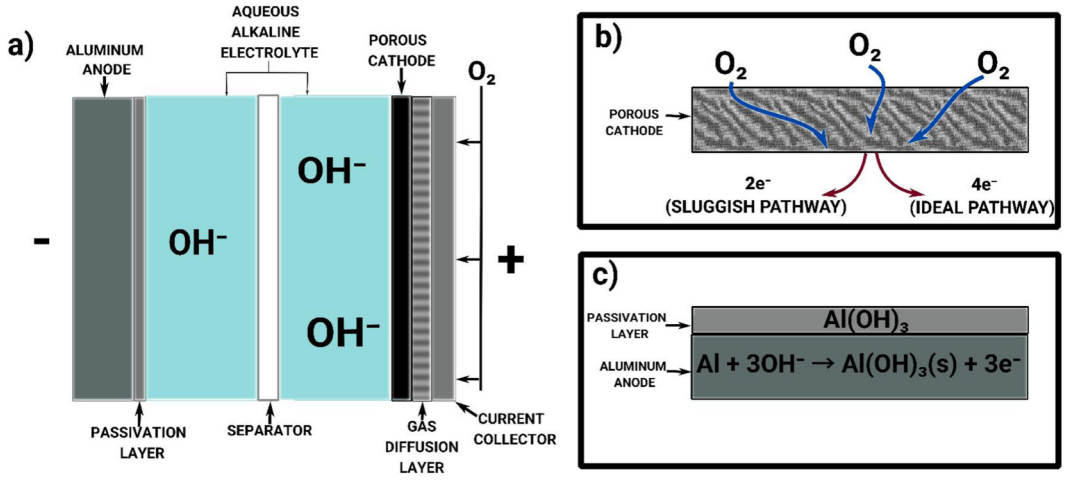

FIGURE 1
(a) Schematic of an Al–air battery showing the Al anode, electrolyte, separator, air cathode, gas diffusion layer and current collector **(b)** ORR possible pathways in cathode. **(c)** Passivation layer formation in aluminum anode.

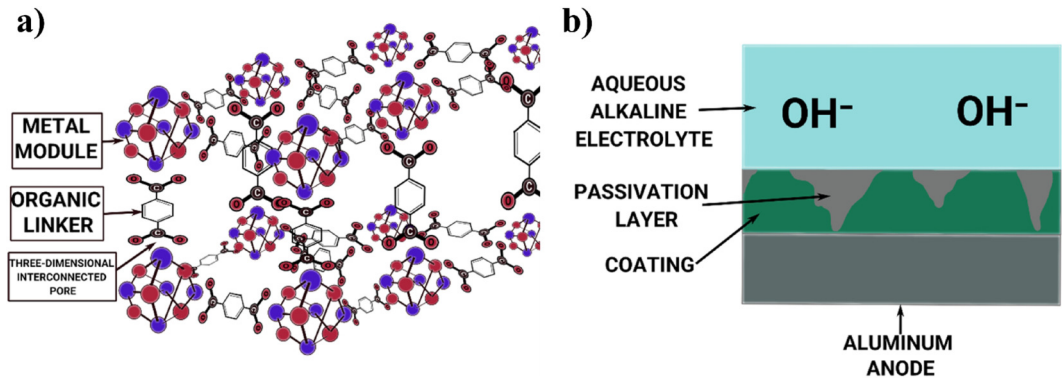

FIGURE 2
(a) Schematic structure of a MOF applied as catalyst for ORR activity. **(b)** Cross-sectional illustration of a coated Al-anode.

nanosheets. The ZnCo-ZIF@GO hybrid demonstrated enhanced ORR electrocatalytic activity, an improved electrical conductivity compared to pristine ZnCo-ZIF.

2.1.4 Limitations

While carbon materials derived from MOFs address the inherent limitations of pristine MOFs (Lu and Su, 2025), however, they encounter obstacles in their application within Al-air cathodes. Firstly, the high-temperature pyrolysis process required for their synthesis is energy-intensive and challenging to scale for industrial production (Zeggai et al., 2025). Moreover, the instability of active sites during extended alkaline operation can result in performance decline (Chen et al., 2019; Xiao et al., 2020). Additionally, although single-metal catalysts offer clearly defined active centers, their effectiveness is frequently constrained by suboptimal adsorption energies of oxygen intermediates. In contrast, bimetallic systems improve catalytic activity through electronic modulation but may suffer from structural complexity and reduced long-term stability. Additionally, in an alkaline electrolyte, the corrosive environment produced by the aluminum anode and the precipitation of solid byproducts, $Al(OH)_3(s)$, obstruct the hierarchical porosity of the MOF-derived cathode (Li et al., 2025). This blockage impedes oxygen diffusion and mass transport at the TPB. Nevertheless, these drawbacks highlight the need for strategies such as flow-cell designs with circulating electrolytes to remove $Al(OH)_3(s)$ precipitates (Teabnamang et al., 2020), along with hierarchical porous architectures that preserve efficient mass transport and catalytic performance (Zhang et al., 2025).

2.2 Coating strategies for aluminum anodes

Surface coating mitigates corrosion and self-passivation of aluminum anode (Al-anode). The protective coating serves as a physical barrier between the anode and the electrolyte that increases polarization resistance, suppressing parasitic reactions while maintaining the ionic transport (Li et al., 2025). These coatings are usually composed of different materials, such as polymers (Gu et al., 2025), carbon-based compounds (Shah, 2021), and metal-

oxides (Sinha et al., 2023), which improve the stability and lifespan of the AAB. Surface modification can control the composition of the surface layer of the Al-anode, thus improving the electrochemical performance.

2.2.1 Coatings based on polymers

Polymer coatings have been widely investigated as protective layers due to their chemical stability and ability to form uniform hydrophobic films. Arumugam et al. (2024) demonstrated that Poly (tetrafluoroethylene) (PTFE) coatings in alkaline electrolyte reduced corrosion current density, extending the anode's discharge duration to over 30 h at 1 mA/cm^2 compared to approximately 5 h for bare aluminum. Despite these benefits, polymer coatings present inherent drawbacks. Hydrophilic variants, such as poly (vinyl alcohol) (PVA), tend to absorb water, swell, and eventually detach due to the accumulation of discharge products underneath. Conversely, while hydrophobic polymers like PTFE or poly (vinylidene fluoride) (PVDF) provide superior corrosion protection, their electrically insulating nature can impede essential ionic transport at high current densities, thereby increasing Ohmic losses. Furthermore, certain polymers like PVDF remain susceptible to long-term chemical degradation, such as defluorination, in strong alkaline environments.

2.2.2 Metal-oxides

Metal-oxides coatings have been also proposed as an anti-corrosion strategy to separate the aggressive electrolyte and protect the Al- anode. These oxide layers can form stable interfacial barriers that regulate aluminum dissolution while still allowing ionic transport across the interface. Metal oxides improve the chemical stability of the anode surface by preventing the rapid formation of insulating aluminum hydroxide layers during discharge (Du et al., 2025). In the study made by Du et al. (2025) demonstrated that applying transition metal oxides (such as V-, Mn-, and Fe-based) significantly reduces the corrosion rate. Specifically, Fe-based coatings showed exceptional 5 V high-voltage stability by forming robust interfacial compounds (Fe–F and Al–N bonds) that lower the corrosion rate by nearly three orders of magnitude. However, a drawback of this strategy is the varying chemical stability of different metal oxides. Under high-voltage polarization, oxides can dissolve and trigger corrosion, or increase interfacial Ohmic impedance, ultimately hindering battery performance (Du et al., 2025).

2.2.3 Coatings based on carbon-based materials

Carbon-based coatings function by creating a conductive porous interfacial layer that inhibits the formation of oxides and minimizes the adherence of $Al(OH)_3$(s), allowing sedimentation, this mechanism ensures the continuous diffusion of essential OH^- ions to the aluminum surface (Hassan et al., 2023; Pino et al., 2016). Pino et al. (2016). demonstrated that carbon black coatings on commercial aluminum alloys extended the anode's discharge duration threefold and achieved specific capacities up to 1210 mAh/g by keeping the surface electrochemically active, improving electron transfer and the decrease in charge transfer resistance (R_{ct}), which enhances reaction kinetics and overall aluminum utilization. However, despite these kinetic advantages, carbon coatings have drawbacks, such as highly porous types, such as pyrolytic graphite, can entrap discharge products within their pores, ultimately obstructing electrolyte access.

2.2.4 Limitations

Single-component coatings have limitations linked to their working mechanisms. Polymer coatings serve as physical barriers that suppress corrosion, but their low electrical conductivity and vulnerability to alkaline swelling restrict ionic transport and long-term stability (Arumugam et al., 2024). Metal-oxide coatings regulate interfacial reactions and improve chemical stability; however, their performance depends on oxide durability, as some dissolve or increase interfacial Ohmic resistance under high polarization (Du et al., 2025). In contrast, carbon-based coatings enhance charge transfer through conductive and porous structures, but they are prone to pore blockage by discharge products and exhibit weak adhesion to aluminum (Pino et al., 2016). These limitations suggest that no single coating can provide protection, transport, and stability simultaneously. Future research should focus on developing multifunctional composite coatings, such as polymer/oxide or carbon/oxide hybrids, to synergistically balance corrosion resistance, conductivity, and durability.

3 Conclusion and future perspectives

The effectiveness and extensive application of aluminum-air batteries are limited by the sluggish ORR and the corrosion/passivation of the Al-anode. While MOF-derived catalysts enhance cathode activity and protective surface coatings mitigate anode corrosion, analysis reveals that their development is insufficient due to research gaps. Firstly, degradation byproducts from anode coatings, such as dissolved metal oxides or defluorinated polymers, may migrate and deactivate sensitive ORR catalytic sites at the cathode. Secondly, the challenge of scaling the energy-intensive pyrolysis of MOFs without causing structural variations between batches remains a major industrial obstacle. Future research should focus on full-cell integration, as a highly active cathode cannot compensate for rapid electrolyte depletion, and a well-protected anode cannot mitigate cathode deactivation.

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References

Arumugam, B. A., Chandra Bose, A., and Ramya, K. (2024). Beyond barrier function: exploring the potential of polymer coatings for high-performance aluminum-air batteries. *ACS Appl. Energy Mater* 7, 7915–7926. doi:10.1021/acsaem.4c01522

Aurbach, D., Lu, Z., Schechter, A., Gofer, Y., Gizbar, H., Turgeman, R., et al. (2000). Prototype systems for rechargeable magnesium batteries. *Nature* 407, 724–727. doi:10.1038/35037553

Chen, X., Wang, N., Shen, K., Xie, Y., Tan, Y., and Li, Y. (2019). MOF-derived isolated Fe atoms implanted in N-Doped 3D hierarchical carbon as an efficient ORR electrocatalyst in both alkaline and acidic media. *ACS Appl. Mater Interfaces* 11, 25976–25985. doi:10.1021/acsami.9b07436

Das, S. K., Mahapatra, S., and Lahan, H. (2017). Aluminium-ion batteries: developments and challenges. *J. Mater Chem. A Mater* 5, 6347–6367. doi:10.1039/C7TA00228A

Dhanabalan, K., Perumalsamy, M., Sriram, G., Murugan, N., Shalu, S. T., Oh, T. H., et al. (2023). Metal–organic framework (MOF)-Derived catalyst for Oxygen Reduction Reaction (ORR) applications in fuel cell systems: a review of Current advancements and perspectives. *Energies (Basel)* 16, 16. doi:10.3390/en16134950

Du, P., Wan, J., Qu, J., Xie, H., Wang, D., and Yin, H. (2024). Passivation and corrosion of Al current collectors in lithium-ion batteries. *Npj Mater Degrad.* 8, 43. doi:10.1038/s41529-024-00453-x

Du, P., Song, Q., Ning, Z., Xie, H., Wang, D., and Yin, H. (2025). A metal oxide coating to suppress the corrosion of aluminum current collectors for high-voltage LiTFSI-based batteries. *Energy Storage Mater* 82, 104569. doi:10.1016/j.ensm.2025.104569

Elia, G. A., Marquardt, K., Hoeppner, K., Fantini, S., Lin, R., Knipping, E., et al. (2016). An overview and future perspectives of aluminum batteries. *Adv. Mater.* 28, 7564–7579. doi:10.1002/adma.201601357

Elia, G. A., Hasa, I., Greco, G., Diemant, T., Marquardt, K., Hoeppner, K., et al. (2017). Insights into the reversibility of aluminum graphite batteries. *J. Mater Chem. A Mater* 5, 9682–9690. doi:10.1039/c7ta01018d

Gu, S., Nie, W., Meng, Q., Chen, X., Zhang, J., Cao, Y., et al. (2025). Stabilizing the aluminum metal anode through polymer coating-enabled regulation of exchange current. *Energy Environ. Sci.* 18, 1477–1488. doi:10.1039/D4EE03542A

Han, J., Zhu, K., and Duan, W. (2023). A comprehensive study on the overall performance of aluminum-air battery caused by anode structure. *Mater Chem. Phys.* 309, 309. doi:10.1016/j.matchemphys.2023.128334

Hassan, S., Nadeem, A. Y., Qaiser, H., Kashif, A. S., Ahmed, A., Khan, K., et al. (2023). A review of carbon-based materials and their coating techniques for biomedical implants applications. *Carbon Lett.* 33, 1171–1188. doi:10.1007/s42823-023-00496-1

He, X., Iqbal, N., Ghani, U., and Li, T. (2024). Potassium ion batteries: recent advancements in anodic, cathodic, and electrolytic materials. *J. Alloys Compd.* 981, 981. doi:10.1016/j.jallcom.2024.173680

Kim, T., Song, W., Son, D. Y., Ono, L. K., and Qi, Y. (2019). Lithium-ion batteries: outlook on present, future, and hybridized technologies. *J. Mater Chem. A Mater* 7, 2942–2964. doi:10.1039/C8TA10513H

Li, Y. W., Zhang, W. J., Li, J., Ma, H. Y., Du, H. M., Li, D. C., et al. (2020). Fe-MOF-Derived efficient ORR/OER bifunctional electrocatalyst for rechargeable zinc-air batteries. *ACS Appl. Mater Interfaces* 12, 44710–44719. doi:10.1021/acsami.0c11945

Li, Y., and Dai, H. (2014). Recent advances in zinc–air batteries. *Chem. Soc. Rev.* 43, 5257–5275. doi:10.1039/C4CS00015C

Li, S., Liu, Z., Wei, X., Wu, H., Mei, H., and Liu, J. (2025). Advanced strategies for suppressing the self-corrosion of the anode in Al–Air batteries. *Met. (Basel)* 15, 15. doi:10.3390/met15070760

Liu, C., Li, F., Ma, L., and Cheng, H. (2010). Advanced materials for energy storage. *Adv. Mater.* 22, 727–731. doi:10.1002/adma.200903328

Liu, Q., Pan, Z., Wang, E., An, L., and Sun, G. (2020). Aqueous metal-air batteries: fundamentals and applications. *Energy Storage Mater* 27, 478–505. doi:10.1016/j.ensm.2019.12.011

Liu, B., Lv, T., Zhou, A., Zhu, X., Lin, Z., Lin, T., et al. (2024). Aluminum corrosion–passivation regulation prolongs aqueous batteries life. *Nat. Commun.* 15, 15. doi:10.1038/s41467-024-47145-3

Lu, X., and Su, P. (2025). Design and application of metal-organic frameworks derivatives as 3-electron ORR electrocatalysts for •OH generation in wastewater treatment: a review. *Chin. Chem. Lett.* 36, 36. doi:10.1016/j.cclet.2025.110909

Macedo, A. A., Liu, Z., Grewal, S., Nelson, A. J., Nasef, Z., Diaz, G., et al. (2021). MOF-derived Co/Cu-embedded N-doped carbon for trifunctional ORR/OER/HER catalysis in alkaline media. *Dalton Trans.* 50, 5473–5482. doi:10.1039/d0dt04000b

Nandi, S., and Pumera, M. (2025). Materials for aluminum batteries: progress and challenges. *Chem. Eng. J.* 517, 164283. doi:10.1016/j.cej.2025.164283

Pino, M., Herranz, D., Chacón, J., Fatás, E., and Ocón, P. (2016). Carbon treated commercial aluminium alloys as anodes for aluminium-air batteries in sodium chloride electrolyte. *J. Power Sources* 326, 296–302. doi:10.1016/j.jpowsour.2016.06.118

Shah, S. M. (2021). Stability enhancement of aluminum-air battery. *J. Mech. continua Math. Sci.* 16, 16. doi:10.26782/jmcms.2021.10.00003

Sinha, A. P., Thomas, T. S., and Mandal, D. (2023). An inorganic-organic protective anode interface towards high-performance Al-air battery. *Energy Storage Mater* 63, 63. doi:10.1016/j.ensm.2023.102988

Teabnamang, P., Kao-Ian, W., Nguyen, M. T., Yonezawa, T., Cheacharoen, R., and Kheawhom, S. (2020). High-capacity dual-electrolyte aluminum-air battery with circulating methanol anolyte. *Energies (Basel)* 13, 13. doi:10.3390/en13092275

Wang, C. Y., Liu, T., Yang, X. G., Ge, S., Stanley, N. V., Rountree, E. S., et al. (2022). Fast charging of energy-dense lithium-ion batteries. *Nature* 611, 485–490. doi:10.1038/s41586-022-05281-0

Xiao, Y., Guo, B., Zhang, J., Hu, C., Ma, R., Wang, D., et al. (2020). A bimetallic MOF@graphene oxide composite as an efficient bifunctional oxygen electrocatalyst for rechargeable Zn-air batteries. *Dalton Trans.* 49, 5730–5735. doi:10.1039/d0dt00976h

Yabuuchi, N., Kubota, K., Dahbi, M., and Komaba, S. (2014). Research development on sodium-ion batteries. *Chem. Rev.* 114, 11636–11682. doi:10.1021/cr500192f

Yang, C., Ma, X., Zhou, J., Zhao, Y., Xiang, X., Shang, H., et al. (2022). Recent advances in metal-organic frameworks-derived carbon-based electrocatalysts for the oxygen reduction reaction. *Int. J. Hydrogen Energy* 47, 21634–21661. doi:10.1016/j.ijhydene.2022.05.025

Zeggai, F. zohra, Ait-Touchente, Z., Bachari, K., and Elaissari, A. (2025). Investigation of metal-organic frameworks (MOFs): Synthesis, properties, and applications - an In-Depth review. *Chem. Phys. Impact* 10, 10. doi:10.1016/j.chphi.2025.100864

Zhang, Y., Tian, Y., Han, Y., Wang, X., and Ma, Z. (2025). Fabrication of N, S co-doped lignin-based hierarchical porous carbon nanocages loaded with binary metal sulfides as high-performance ORR/OER cathode materials for Zn-air batteries. *J. Energy Storage* 114, 114. doi:10.1016/j.est.2025.115822