Review Article

Journal of Environmental Nanotechnology

A Review on Metal-air Batteries with an Emphasis on the Electrochemical Performance of Aluminum-air Batteries

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Received: 01.04.2025 Accepted: 20.06.2025 Published: 30.06.2025

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ABSTRACT

Enhancing global decarbonization programs and assisting the transition to sustainable energy systems are both made possible by energy storage technology. Among the several electrochemical storage technologies, batteries stand out for their adaptability and their role in mitigating climate change. One potential alternative for next-generation energy storage is rechargeable metal-air batteries, which have environmental benefits and a high energy density. Electric cars, portable electronics, and large-scale energy storage for renewable source integration are just a few of the many uses for these batteries. With an emphasis on the electrolyte, metal anode, and air cathode, this paper offers a thorough evaluation of current advancements in metal-air battery technology. Systems using zinc, magnesium, sodium, lithium, and air provide high-performance metal-air batteries. There are clear benefits to energy efficiency and environmental friendliness offered by each of these methods. The promising combination of low production costs and high energy density has piqued the interest of many researchers in aluminum-air batteries. They are also being studied for ways to enhance their electrochemical properties, which might make them useful in future energy storage systems. Recent advances and strategic techniques in metal-air battery research are outlined in this study, which could help their greater implementation in electrification and energy storage technologies.

Keywords: Al-air battery; Metal-air battery; Battery.

1. INTRODUCTION

The issues associated with fuel-based energy systems, including environmental pollution and the depletion of natural resources, have led to a heightened focus on research aimed at developing clean and renewable energy sources (Choi *et al.* 2021; Liu *et al.* 2021a). Electricity is considered a sustainable alternative to fossil fuels and is classified as a form of green energy. Electrochemical energy storage devices are anticipated to significantly influence the development of future energy networks (Asmare *et al.* 2024). The growth of electrification, especially within the transportation sector, is expected to play a role in mitigating global warming. The energy storage system (ESS) consists of fuel cells, electrochemical capacitors, and rechargeable batteries. Rechargeable batteries are extensively employed in a range of electronic devices, such as electric vehicles and portable electronics (Liu *et al.* 2017).

Metal-air batteries (Fig. 1) are a promising technology that has the potential to deliver high-performance and sustainable energy storage solutions. One of the primary benefits of these batteries compared to traditional lithium-ion batteries is their considerably greater theoretical energy densities. Metal-air battery variants encompass zinc-air (Zn-air), lithium-air (Li-air), aluminum-air (Al-air), magnesium-air (Mg-air), and sodium-air (Na-air) batteries (Salado *et al.* 2022; Wang *et al.* 2019a). This characteristic enhances their suitability for applications, including electric vehicles, large-scale energy storage systems, and portable electronic devices (Zhang *et al.* 2014; Li *et al.* 2020; Wang *et al.* 2022). The core operational principle of metal-air batteries consists of the oxidation process occurring at the metal anode and the reduction of oxygen taking place at the air cathode. The unique design of these batteries allows them to draw oxygen directly from the surrounding air, which eliminates the requirement for a bulky cathode chamber and contributes to their high energy density (Wang *et al.* 2022; Olabi *et al.* 2021). The air cathode is designed to be porous, facilitating efficient oxygen diffusion and integrating catalysts that improve oxygen reduction reactions (ORR) (Olabi *et al.* 2021).

Metal-air batteries possess considerable potential for commercialization; however, various technological challenges presently obstruct their broad

adoption. Primary considerations encompass the performance and stability of the metal anode, the efficiency of the air cathode, and the properties of the electrolyte (Cheng *et al.* 2012). Key challenges that need to be addressed encompass the slow kinetics of the oxygen evolution reaction (OER) occurring at the air cathode, in addition to issues related to corrosion and dendritic growth at the metal anode (Cheng *et al.* 2012; Blurton *et al.* 1979)

Recent studies have concentrated on novel designs and cutting-edge materials to address these challenges. Recent advancements in catalyst development include the utilization of metal oxides, noble metals, and carbon-based compounds to improve the electrochemical performance of the air cathode (Wang *et al.* 2022; Olabi *et al.* 2021). Furthermore, initiatives are underway to enhance the stability and conductivity of electrolytes, along with the design of versatile flow battery systems (Li *et al.* 2017; Wang *et al.* 2022; Rahman *et al.* 2013). The objective of these studies is to improve the overall efficiency and lifespan of metal-air batteries. Among metal–air systems, aluminum–air (Al–air) batteries are particularly attractive due to aluminum's high theoretical specific energy (~8100 Wh/kg), natural abundance, low cost, and non-toxicity (Zhang *et al.* 2020). Aluminum is the third most abundant element in the Earth's crust and is widely used in various industries. Its use in air batteries opens pathways for lightweight and efficient energy storage, especially in electric vehicles, military, and off-grid applications.

Despite these advantages, several technical challenges hinder the commercialization of Al–air batteries. The key issues include the formation of a passive oxide layer on the aluminum anode, which restricts further electrochemical reactions; hydrogen evolution reaction (HER) in aqueous electrolytes; self-corrosion of the anode; and the irreversibility of the cell reaction, which typically makes Al–air batteries primary (non-rechargeable) systems. Moreover, the choice and stability of electrolytes (alkaline, neutral, or ionic liquids) greatly influence the battery's performance, cycle life, and safety.

To overcome these limitations, extensive research has been carried out focusing on material modification (such as Al-alloy anodes), electrolyte engineering, and air cathode improvements to enhance the electrochemical performance, corrosion resistance, and overall efficiency of Al–air systems. Hybrid and semi-fuel-cell configurations are also under exploration to make the system more sustainable and potentially rechargeable. This review aims to systematically explore the fundamentals, recent progress, and technological challenges associated with metal–air batteries, with a special emphasis on the electrochemical behavior and performance optimization of aluminum–air batteries. It further discusses strategies adopted to address critical issues and provides future directions for research and development in this field.

In summary, metal-air batteries present significant potential for advancements in energy storage technology. Their design provides substantial energy storage capacity, with the potential for cost-effectiveness and environmental sustainability. Extensive research and development are required to address current technological barriers and facilitate their practical implementation in various applications (Zhang *et al.* 2013; Han *et al.* 2018).

2. METAL-AIR BATTERY

The combination of metal-air batteries' low cost, low environmental impact, and high theoretical energy density makes them an attractive candidate for use in next-generation energy storage systems. Electric cars, consumer gadgets, and large-scale energy storage systems are among the possible uses. However, before reaching economic viability, a number of technical hurdles must be overcome. The potential energy densities of metal-air batteries, such as zinc-air and lithium-air, are far greater than those of lithium-ion batteries. Their unique quality makes them ideal for use in electric cars and grid energy storage (Liu *et al.* 2019; Olabi *et al.* 2021; Cheng *et al.* 2012; Blurton *et al.* 1979). Slow reaction kinetics at the air electrode, dendritic development on the metal anode, and hydrogen evolution corrosion are some of the obstacles to the commercialization of metal-air batteries (Olabi *et al.* 2021; Blurton *et al.* 1979). To improve the charge and discharge capacity of these batteries, it is necessary to improve the design of the air electrodes, metal electrodes, electrolytes, and separators (Zhang *et al.* 2013a; Wang *et al.* 2019b; Li *et al.* 2017; Olabi *et al.* 2021; Blurton *et al.* 1979). Extensive research has been conducted on both aqueous (Zn-air) and non-aqueous (Li-air) systems, with distinct advantages and disadvantages for each. The energy densities of non-aquatic systems are greater, but the safety and environmental advantages of aqueous systems are well-recognized (Wang *et al.* 2019b; Liu *et al.* 2019; Olabi *et al.* 2021).

Modern technology has allowed for the development of metal-air flow batteries and flexible fiber-shaped metal-air batteries, which integrate the structural benefits of flow batteries with the high energy density of metal-air batteries (Han *et al.* 2018; Rahman *et al.* 2013). The choice of catalysts used in the air cathode has a substantial impact on the efficiency of metal-air batteries. Various materials, including carbon-based compounds, metal oxides, and noble metals, are being investigated at the moment to improve oxygen reduction and evolution processes (Wang *et al.* 2019c; Olabi *et al.* 2021).

In order to encourage the broad use of metal-air batteries, future studies will look into novel battery designs, optimize material design, and solve existing technological issues (Zhang *et al.* 2013b; Li *et al.* 2017; Cheng *et al.* 2012; Blurton *et al.* 1979). These batteries provide a strong case for potential energy storage solutions in the future due to their versatile design and high energy density. To make metal-air batteries commercially viable, there must be significant progress in materials science, new battery designs, and our knowledge of electrochemical processes.

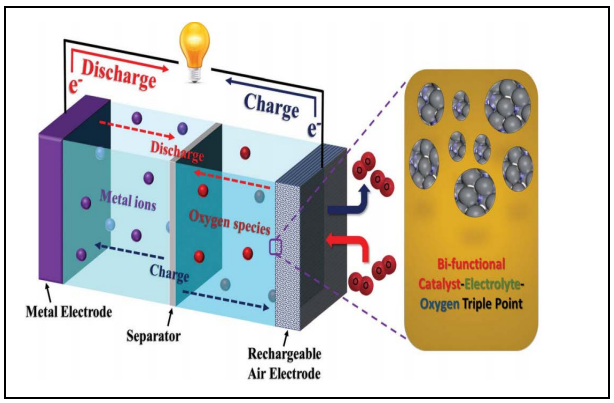


Fig. 1: Basic structure of metal air battery

Several sequential steps are involved in discharging a metal-air battery. A reduction process involving oxygen happens at the cathodic electrode, leading to the creation of hydroxide ions. The anodic electrode's metal undergoes oxidation at the same time, turning it into metal ions. By a gas diffusion layer, oxygen is injected into the battery by diffusion processes. Metallic ions are formed, and electrons are released during the oxidation process of metals. This process generates electricity as the electrons flow via an external circuit. All the while, the electrolyte contains the dissolved metallic ions.

As the battery is charged, the reactions reverse direction. In an electrolyte, solid metal is formed when metal ions are reduced at the anode. At the same time, oxygen gas is released when hydroxide ions at the cathode undergo oxidation. In a cyclical process, metal-air batteries are able to be recharged. The key properties of various metal-air batteries are summarized in Table 1.

2.1 Zinc Air Battery

The high energy density, cheap cost, and excellent safety profile of zinc-air batteries make them a promising candidate for future energy storage systems. Electrolytes, air electrodes, and electro-catalysts are the main components of zinc-air batteries, which are examined in this paper. It also emphasizes recent advancements and the challenges encountered in their development. The air electrode is essential in influencing the performance efficiency and cost-effectiveness of zinc-air batteries.

Table 1. Properties of different metal-air battery

Type of metal air battery	Theoretical energy density (Wh/Kg)	Theoretical energy density excluding Oxygen (Wh/Kg)	Cell voltage (V)	Specific energy (KWh/L)
Zinc air battery	1086	1352	1.65	3750
Sodium air battery	1601	2716	2.33	1580
Lithium air battery	5220	11238	2.91	3460
Magnesium air battery	2848	6098	2.77	2850
Aluminum air battery	2784	8091	2.7	2790
Silicon air battery	2334	8001	2.08	3750

Recent research highlights the significance of integrating efficient oxygen electrocatalysts into the air electrode to improve overall battery performance. Innovative electrode designs and enhanced oxygen electrocatalysts have been created to enhance the performance of both primary and rechargeable zinc-air batteries (Ye *et al.* 2020). Furthermore, surface and interface nanoengineering has been recognized as a vital element in improving power density, stability, and rechargeability by tackling the intricate three-phase interfacial reactions (Pan *et al.* 2018).

Zinc–air batteries operate using zinc metal as the anode and oxygen from air at the cathode. The reactions depend on the electrolyte, commonly aqueous alkaline (e.g., KOH).

Anode (Negative Electrode):

Oxidation Reaction:

$$Zn\ (s) + 4OH^- \rightarrow Zn(OH)_4^{2-} + 2e^-$$

$$Zn(OH)_4^{2-} \rightarrow ZnO\ (s) + 2\ OH^- + H_2O$$

Cathode (Positive Electrode):

Oxygen Reduction Reaction (ORR):

$$O_2 + 2\ H_2O + 4e^- \rightarrow 4\ OH^-$$

Overall Reaction:

$$2Zn + O_2 \rightarrow 2ZnO$$

Table 2. Aspect of Zinc–air Battery

Aspect	Zinc–air Battery
1. Reaction Kinetics	• The ORR at the air cathode is sluggish and typically requires bifunctional catalysts (e.g., MnO_2, Co_3O_4, Pt). • The Zn oxidation is relatively fast. • Rechargeable Zn-air faces challenges with oxygen evolution reaction (OER) on charging.
2. Electrolyte Stability	• Aqueous alkaline electrolytes (like KOH) are common but suffer from carbonation (reaction with CO_2 from air). • Leads to precipitation of carbonates, which reduces conductivity. • Electrolyte drying out is also a concern in open systems.
3. Electrode Challenges	• Anode: Zinc can suffer from dendrite growth, passivation, and shape change during cycling. • Cathode: Requires porous, hydrophobic, and catalyst-rich design. • Managing water and air flow is critical in cathode performance.

The effective catalysis of the oxygen evolution process (OER) and the oxygen reduction reaction (ORR) is made possible by bifunctional electrocatalysts, which are vital in rechargeable zinc-air batteries. New research shows that N-doped carbon nanosheets with ultra-fine FeNi nanoparticles improve the catalytic performance, with increased specific capacity and remarkable cycle stability (Zhou *et al.* 2020). Hybrid zinc-air and zinc-silver (Zn-Ag) battery technologies have shown promising results through the integration of both systems, resulting in enhanced energy stability and efficiency (Li *et al.* 2021).

The electrolyte serves as a critical element that affects the capacity, cycle life, and overall durability of Zn-air batteries. Recent advancements in electrolyte design have concentrated on enhancing the efficiency of aqueous ionic liquids and quasi-solid-state flexible electrolytes that function effectively at room temperature (Tan *et al.* 2018). Improving battery performance necessitates the optimization of two critical reaction interfaces: the interaction between the electrolyte and zinc, as well as the interaction among air, catalyst, and electrolyte.

Research on flexible and wearable zinc-air batteries has been heavily concentrated due to the rising demand for these types of devices. The improvement of high-performance flexible Zn-air batteries has been made possible by recent advancements in flexible air electrodes, which exhibit higher electrocatalytic activity and stability. Improving mechanical flexibility and conductivity, significant gains have been made by in-situ connecting stretched Co4N structures with entangled N-C fibers (Chen *et al.* 2020; Meng *et al.* 2018) New wearable energy storage systems are smaller, more efficient, and safer thanks to the invention of direct all-solid-state rechargeable zinc-air batteries (Meng *et al.* 2016).

Several obstacles must be overcome before zinc-air batteries may be mass-produced for commercial use, even though great strides have been made in this direction. For widespread use, it is necessary to develop non-noble metal dual-functional catalysts that are both inexpensive and display strong ORR and OER activity, as well as improved durability (Kumar *et al.* 2023). To further enhance the performance of Zn-air batteries, further study is needed to refine the assembly, manufacturing, and structural design of air electrodes (Cao *et al.* 2019).

When it comes to energy storage (Fig. 2), zinc-air batteries show a lot of promise for the future. We must overcome the existing technological obstacles and facilitate the manufacturing of high-performance, cost-effective, and durable Zn-air batteries through ongoing research and development in air electrodes, catalysts, and electrolytes.

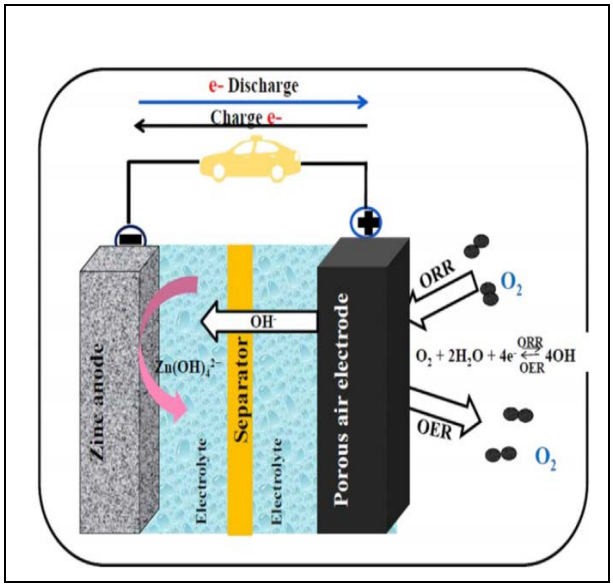


Fig. 2: The schematic diagram of the typical rechargeable zinc air battery. OER, oxygen evolution reaction; ORR, oxygen reduction reaction (Worku *et al.* 2020)

2.2 Sodium Air Battery

Sodium-air batteries represent a viable alternative to lithium-based energy storage systems, attributed to the cost-effectiveness and widespread availability of sodium. This document presents a comprehensive analysis of the recent developments and obstacles related to sodium-air battery technology, synthesizing findings from various research

efforts. Sodium-air batteries, commonly known as Na-air batteries, are viewed as a potential alternative to lithium-air batteries, attributed to their similar electrochemical characteristics, reduced cost, and the higher natural availability of sodium (Zhang *et al.* 2021a; Khan *et al.* 2020). The battery function utilizing a sodium metal anode and an air cathode, with various discharge products generated based on the specific electrolyte employed.

Na-air batteries are categorized into two types according to their electrolyte: aqueous and non-aqueous. Extensive studies have been conducted on these batteries, which are characterized by their high energy density and typically utilize organic electrolytes. Challenges such as the formation of insoluble discharge byproducts, including sodium oxide and sodium superoxide, impede their efficiency and cyclability (Ha *et al.* 2014*;* Yin *et al.* 2016*;* Kim *et al.* 2018*;* Liu *et al.* 2021d*;* Khan *et al.* 2016*;* Yin *et al.* 2014). Aqueous Na-air batteries generate highly soluble discharge products, such as sodium hydroxide (NaOH), which contribute to improved cycle stability and energy efficiency (Zhang *et al.* 2021a; Khan *et al.* 2020; Ha *et al.* 2014; Yin *et al.* 2016; Kim *et al.* 2018; Liu *et al.* 2021d). While these advantages are notable, challenges persist, including the instability of aqueous electrolytes and the requirement for highly efficient electrocatalysts (Zhao *et al.* 2014).

Recent research has concentrated on addressing these limitations to enhance the performance and practicality of Na-air batteries. Hybrid systems that integrate aqueous and non-aqueous electrolytes demonstrate potential by merging the advantages of both types—utilizing the improved solubility of aqueous electrolytes alongside the increased energy density of non-aqueous electrolytes (Zhang *et al.* 2021a; Yin *et al.* 2014). The creation of effective electrocatalysts that can promote both the oxygen reduction reaction (ORR) and the oxygen evolution reaction (OER) is essential. Studies indicate that single-crystalline $Bi_2Ru_2O_7$ pyrochlore nanoparticles function as highly effective electrocatalysts for hybrid Na-air batteries (Yin *et al.* 2016). Furthermore, innovative methods, including gel electrolytes and quasi-solid-state configurations, have been investigated to improve battery lifespan and safety, targeting critical challenges such as dendrite formation and sodium anode corrosion (Yin *et al.* 2016; Zhao *et al.* 2014).

Sodium–air batteries typically operate with oxygen from the air as the cathode reactant and metallic sodium as the anode. The overall reaction depends on the discharge product, which can vary based on the electrolyte and operating conditions (e.g., NaO_2 vs. Na_2O_2 vs. Na_2O).

Anode (Negative Electrode):

Oxidation reaction:

$$Na \rightarrow Na^+ + e^-$$

Metallic sodium is oxidized, releasing electrons and forming sodium ions.

Cathode (Positive Electrode):

The oxygen reduction reaction (ORR) depends on the discharge product:

Common case (formation of sodium superoxide, NaO_2):

$$O^2 + Na^+ + e^- \rightarrow NaO_2$$

Overall Cell Reaction:

$$Na + O_2 \rightarrow NaO_2$$

Alternative products (like Na_2O_2 or Na_2O) may form under different conditions.

Table 3. Aspect of Sodium-air Battery

Aspect	Sodium-air Battery
1. Reaction Kinetics	• Slower kinetics for the ORR and OER (oxygen evolution reaction) compared to lithium-air due to heavier Na^+. • Reaction product (e.g., NaO_2) forms as solid, can block active sites. • Requires efficient catalysts to improve kinetics.
2. Electrolyte Stability	• Na reacts aggressively with most organic solvents. • Electrolyte decomposition is a major issue, especially in the presence of reactive oxygen species (like superoxide O_2^-). • Ionic liquids and solid-state electrolytes are being explored.
3. Electrode Challenges	• Anode: Sodium metal is highly reactive and can form dendrites leading to short-circuiting. • Cathode: Need to manage solid NaO_2 or Na_2O_2 deposition, which clogs pores and blocks ORR. • High surface area carbon is used but may degrade over cycles.

Despite notable progress, various obstacles continue to hinder the broad implementation of Na-air batteries. Maintaining long-term electrolyte stability and ensuring compatibility with both the air cathode and sodium anode is essential for reliable operation (Ha *et al.* 2014*;* Khan *et al.* 2017). Improving safety and longevity, especially in practical environments where batteries interact with ambient air, represents a significant focus of research. Strategies being developed to mitigate these challenges include protective coatings and advanced electrolyte formulations (Kim *et al.* 2018; Zhao *et al.*

2014). Additionally, the optimization of the air electrode structure is critical for enhancing gas diffusion and controlling the formation of discharge products, which in turn improves overall battery performance (Liu *et al.* 2021b).

Sodium-air batteries offer a cost-efficient and high-energy-density option compared to lithium-based energy storage systems, with potential applications across multiple sectors. Overcoming the existing technological barriers necessitates ongoing research and development in the areas of electrolyte chemistry, electrocatalyst innovation, and electrode design. Addressing these challenges may enable Na-air batteries to significantly contribute to the future of sustainable energy storage, offering a practical and cost-effective solution to accommodate increasing energy demands.

2.3 Lithium-air Battery

The capability of lithium-air batteries to store more energy than conventional lithium-ion batteries has piqued a lot of people's interests in these batteries. Potentially revolutionizing energy storage systems for electric cars and portable electronic gadgets, these batteries have a theoretical energy density that is similar to gasoline. While they have great promise, there are a number of scientific and technical obstacles that prevent their widespread use. With an emphasis on recent advances and major obstacles, this article provides a thorough review of the present state of research on lithium-air batteries.

For non-aqueous lithium-air cells, the fundamental obstacle is to achieve reversible chemistry that keeps efficiency high throughout cycles. Both capacity and cyclability are limited by the accumulation of electrically resistive discharge products, such as lithium peroxide (Li_kO_k). To reduce the deterioration induced by water exposure, lithium-protective membranes must be utilized in aqueous lithium-air cells. These membranes provide extra design hurdles due to their thick, heavy, and highly resistive characteristics.

When developing Li-air batteries, it is crucial to ensure that electrolytes are stable when exposed to oxygen and lithium metal. Traditional solid electrolytes can degrade over time, leading to reduced performance. More stable solid-state electrolytes have been the focus of recent research. One promising candidate is lithium-ion-exchanged zeolite X (LiX) membranes, which show promise for enhancing stability and cycle life. Redox kinetics of oxygen at the positive electrode are sluggish, which reduces cycle life and reduces energy efficiency. Enhancing electrochemical performance and making discharge product breakdown more reversible are two areas of active study.

Li–Air batteries use lithium metal as the anode and oxygen from air as the cathode reactant. The reactions depend on the discharge product—most commonly Li_2O_2 (lithium peroxide) in non-aqueous systems.

Anode (Negative Electrode):

Oxidation Reaction:

$$Li \rightarrow Li^+ + e^-$$

Lithium metal is oxidized to lithium ion, releasing one electron.

Cathode (Positive Electrode):

In non-aqueous systems (most common):

$$O_2 + 2Li^+ + 2e^- \rightarrow Li_2O_2$$

In aqueous systems:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

Or

$$O_2 + 4Li^+ + 4e^- \rightarrow 2Li_2O$$

Overall Reaction (non-aqueous):

$$2Li + O_2 \rightarrow Li_2O_2$$

Table 4. Aspect of Sodium-air Battery

Aspect	Lithium–air Battery
1. Reaction Kinetics	• Oxygen reduction reaction (ORR) and oxygen evolution reaction (OER) are slow and complex. • Formation/decomposition of Li_2O_2 has high overpotentials. • Needs high-performance catalysts (e.g., Ru, MnO_2) for reversibility.
2. Electrolyte Stability	• Non-aqueous electrolytes (like ethers or carbonates) degrade due to reaction with O_2^- and Li_2O_2. • Decomposition forms unwanted side-products (e.g., Li_2CO_3). • Electrolyte evaporation, instability with moisture/O_2 limits lifespan.
3. Electrode Challenges	• Anode: Lithium is highly reactive; forms dendrites, risks short-circuiting. • Cathode: Insulating Li_2O_2 clogs pores, limiting O_2 diffusion. • Cathode must be porous, conductive, and chemically/electrochemically stable.

When it comes to lithium-air batteries, contamination may affect both the aqueous and non-aqueous varieties. When moisture is present in systems that are not aqueous, it may cause unwanted reactions to start inside the organic electrolyte and lithium metal anode, which in turn reduces their efficiency. Some

have suggested hybrid and aqueous arrangements as solutions, but they, too, come with their problems (Chen *et al.* 2021b). There have been significant strides in creating new materials for air batteries that use lithium dioxide. An example of a gel electrolyte with improved battery life and bidirectional transition capabilities contains redox mediators like lithium and sheets of lower-density polyethylene (Christensen *et al.* 2011). Improved electrochemical performance has been seen with the use of solid-state electrolytes that are stable and flexible, notably those produced from zeolites (Bruce *et al.* 2011).

New insights into the complex electrochemical and transport processes of Li-air batteries have emerged from advances in mathematical modeling and simulation. New materials and battery topologies may be informed by the investigations, which help to understand better the reaction kinetics, side reactions, and solid discharge product generation at the electrodes (Grande *et al.* 2014). To address the drawbacks of non-aqueous systems, researchers have looked at hybrid and aqueous Li-air batteries. A solid electrolyte is often used in the designs to protect the lithium-metal anode, and an aqueous catholyte and an air electrode are also included. While these techniques show promise for improving energy density and cycle life (Chen *et al.* 2021b). they call for other improvements, such as the development of a Li^+-Li-conducting buffer layer, to be fully realized.

The advancement of lithium-air battery research hinges on addressing essential challenges associated with electrode kinetics, electrolyte stability, and material durability. The ongoing advancement of high-performance, stable materials, coupled with the implementation of sophisticated modeling techniques, is essential for realizing their complete potential. Moreover, it is necessary to investigate innovative battery architectures and improved safety measures for lithium anodes to advance this technology toward commercial viability (Chang *et al.* 2021*;* Chi *et al.* 2021*;* Tan *et al.* 2017*).*

Li-air batteries exhibit the potential to surpass traditional lithium-ion batteries, fostering optimism regarding their application in future energy storage systems. Significant obstacles must be addressed, including contamination control, electrolyte stability, and reversible chemistry. Recent advancements in modeling, materials science, and hybrid configurations present promising solutions; however, additional research and development are crucial to commercialize Li-air batteries and fully harness their potential.

2.4 Magnesium-Air Battery

A lot of people are interested in magnesium-air (Mg-air) batteries because they are cheap, they are suitable for the environment, and they are economically viable. Focusing on the anode materials, electrolyte compositions, and air cathode catalysts, this paper provides a thorough review of current developments in magnesium-air battery research and development while also highlighting the significant obstacles that still need to be overcome

2.4.1 Anode Materials and Challenges

In magnesium-air batteries, the anode is generally composed of magnesium or magnesium alloys instead of pure magnesium. Pure magnesium anodes experience elevated corrosion rates and the development of passivation layers, including magnesium hydroxide ($Mg(OH)_2$). These factors contribute to a decrease in active surface area and overall efficiency (Zhang *et al.* 2013). Extensive research has been conducted on various magnesium alloys to address these issues. The Mg–0.1 wt% Ca alloy demonstrates enhanced corrosion resistance and discharge performance when compared to high-purity magnesium and commercially available Mg alloys. Furthermore, the development of a unique $Mg_{64}Zn_{36}$ alloy has been achieved by minimizing hydrogen evolution through Zn alloying, showcasing remarkable discharge capacity and efficiency (Dinesh *et al.* 2014*)*.

2.4.2 Electrolyte Composition and Optimization

The selection of electrolytes is critical to the performance of magnesium-air batteries. Conventional aqueous electrolytes frequently result in suboptimal anode utilization and significant corrosion issues. Researchers have investigated alternative electrolyte compositions to address these challenges. Magnesium triflate ($Mg(OTf)_2$)-based aqueous electrolytes have been observed to mitigate anode corrosion and enhance specific capacity through the formation of a magnesium fluoride (MgF_2) protective layer (Deng *et al.* 2018). Water-soluble graphene (WSG) has demonstrated an enhancement in electrochemical activity and discharge performance when utilized in NaCl-based electrolytes (Song *et al.* 2023). Additionally, the incorporation of robust complexing agents within the electrolyte has demonstrated efficacy in activating the magnesium anode and enhancing the delivered potential (Meganathan *et al.* 2015).

Magnesium–air batteries use metallic magnesium as the anode and oxygen from air as the cathode reactant, operating typically in aqueous alkaline electrolytes (like NaOH or KOH).

Anode (Negative Electrode):

Oxidation Reaction:

$$Mg\ (s) \rightarrow Mg^{2+} + 2e^-$$

Magnesium is oxidized, releasing two electrons and forming Mg^{2+} ions.

Cathode (Positive Electrode):

Oxygen Reduction Reaction (ORR):

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Overall Cell Reaction:

$$2Mg + O_2 + 2H_2O \rightarrow 2Mg(OH)_2$$

2.4.3 Air Cathode Catalysts and Oxygen Reduction Reaction (ORR)

An integral part of Mg-air batteries, the air cathode facilitates the oxygen reduction process (ORR), which in turn affects the battery's efficiency. Nanoporous graphene doped with nitrogen (N-doped) is one of many advanced catalytic materials that have been the subject of substantial study. With its three-dimensional porous structure and ORR performance that rivals platinum, N-doped graphene has become an attractive option for Mg-air batteries in both solid-state and aqueous forms. In addition, OM-NCNF-FeNx, which are open-mesoporous carbon nanofibers combined with atomic Fe-Nx, have been designed to serve as oxygen electrodes with good performance, showing improved flexibility, discharge capacity, and voltage (Xi *et al.* 2023).

2.4.4 Challenges

There have been great strides, but there are still a number of obstacles that make Mg-air batteries impractical. The main issues include:

- Poor anodic performance due to the formation of passivation layers on magnesium anodes (Zhnag *et al.* 2013).
- Slow ORR kinetics at the air cathode, which limits overall battery efficiency (Zhang *et al.* 2013).
- Formation of dielectric MgO or MgO_2 layers on the air-breathing cathode, leading to sluggish reaction kinetics and reduced rechargeability (Tong *et al.* 2021).

The rechargeability and efficiency of Mg-air batteries may be improved by the development of bi-functional catalysts that enable oxygen evolution and reduction processes concurrently (Chen *et al.* 2021a). As a versatile, low-cost power source with a high energy density, magnesium-air batteries have a lot of promise. Making these batteries economically feasible and high-performing requires addressing current limits in anode materials, electrolyte formulas, and air cathode catalysts. To take Mg-air battery technology to the next level and make it widely used, research and innovation must continue.

2.5 Aluminum-air Battery

The extraordinary energy density, low cost, and promising future of aluminum-air (Al-air) batteries as environmentally friendly energy storage systems have garnered a lot of interest. Anode oxidation and cathode oxygen reduction reactions (ORR) are the basis of these batteries' operation, which makes them an attractive substitute for conventional lithium-ion batteries. The optimization of electrolytes, cathode efficiency, and anode corrosion are three obstacles that prevent their broad use. Recent studies have attempted to resolve problems with alloying agents, anode deformation, and electrolyte composition to increase the electrochemical stability of Al-air batteries. Mechanical deformation of the anode is a key component impacting electrochemical performance. Research has shown that peak power densities in aluminum anodes are reduced when the dislocation density is raised using methods such as cold rolling. The inverse connection between hardness and electrochemical efficiency was shown by the peak power densities of 252, 219, and 174 mW cm^{-2}, respectively, for anodes with dislocation densities of 3.0 x 10^{15} m^{-2}, 6.5 x 10^{15} m^{-2}, and 19 x 10^{15} m^{-2}, respectively (Cheng *et al.* 2018). Mechanical strength enhances structural integrity, but it limits anodic dissolution and increases passivation layer development, which negatively influences battery performance.

Table 5. Aspect of Sodium-air Battery

Electrolyte Type	Advantages	Disadvantages
Alkaline (KOH/NaOH)	Higher conductivity, longer shelf life, and greater stability	CO_2 sensitivity, corrosion, HER, poor rechargeability
Neutral	Safer, lower corrosion, potentially rechargeable	Slower kinetics, lower conductivity
Ionic Liquids	Stable, low volatility, reduced side reactions	Costly, viscous, lower ionic mobility
Gel Electrolytes	Safer, flexible, reduced leakage	Limited conductivity and long-term stability

The electrochemical performance of aluminum anodes is greatly improved by alloying elements, which increase discharge efficiency and decrease corrosion resistance. In an effort to maximize battery performance, many alloy compositions have been investigated. Because of their capacity to reduce passivation effects and increase anodic dissolution, Al-Mg-Sn alloys have shown better battery discharge properties than pure aluminum (Wang *et al.* 2020). As an alternative to high-performance Al-air batteries, Al-In

and Al-Sn alloys have been discovered to decrease significantly self-corrosion rates and enhance electrochemical activity. Although Al-Ga alloys have good electrochemical activity, they are not very useful because of their high rate of self-corrosion (Ma *et al.* 2018). Manganese, when added to Al-Zn-In-Sn-Mg-Mn alloys, stabilizes the aluminum matrix and prevents localized corrosion effects, which in turn lowers self-corrosion and improves energy density (Wang *et al.* 2019c). Also, in 4M NaOH ethanol-water solutions, Al-Mg-Sn-In alloys have shown outstanding electrochemical characteristics, with lower rates of self-corrosion and enhanced anodic utilization because of the ethanol's role in moderating hydrogen evolution events (Gelman *et al.* 2017).

Another important consideration for Al-air battery performance is electrolyte choice. While traditional aqueous electrolytes like NaOH and KOH are great conductors, they might reduce battery performance due to hydrogen evolution and severe anode corrosion. This has prompted the investigation of dual-electrolyte systems, which have shown promising results in lowering self-corrosion rates and improving electrochemical efficiency (Sun*et al.* 2020). One such system incorporates porous polyacrylic acid (PAA) hydrogel with 4M KOH. Research has also shown that alkaline electrolytes, such as NaOH and NaCl, work better in batteries when the particle sizes of the aluminum are reduced. This is because smaller grains have a greater impact on dissolving activity and reduce passivation effects, which means that the batteries last longer (Sun *et al.* 2020a).

Aluminum–Air batteries use aluminum metal as the anode and oxygen from air as the cathode reactant, typically in aqueous alkaline electrolytes like NaOH or KOH.

Anode (Negative Electrode):

Oxidation Reaction:

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

Or in full:

$$Al + 3H_2O \rightarrow Al(OH)_3 + 32H_2\uparrow$$

This shows competing hydrogen evolution reaction (HER) in aqueous media.

Cathode (Positive Electrode):

Oxygen Reduction Reaction (ORR):

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Overall Cell Reaction:

$$4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3$$

Table 6. Aspect of Al–air battery

Aspect	Al–air Battery
1. Reaction Kinetics	• Al oxidation is thermodynamically favorable but suffers from kinetic hindrance due to passive Al_2O_3 layer. • ORR is sluggish, requiring catalysts (e.g., Ag, Pt, MnO_2). • Competing HER also impacts efficiency.
2. Electrolyte Stability	• Uses alkaline aqueous electrolytes, which dissolve Al_2O_3 but can also corrode Al. • Electrolyte reacts with CO_2 to form carbonates, reducing performance. • Water loss and pH changes affect long-term operation.
3. Electrode Challenges	• Anode: Rapid formation of $Al(OH)_3$ or Al_2O_3 forms a passivation layer, reducing reactivity. • Cathode: Needs to maintain high oxygen permeability and water management. • Electrolyte leakage and corrosion are concerns.

The ORR, which affects the total energy production, is greatly aided by the cathode in Al-air batteries. Oxygen vacancy defect-engineered MnO_2 catalysts have been created to boost cathodic efficiency (Gelman *et al.* 2017). Oxygen vacancies increase ORR kinetics by increasing adsorption and activation. In addition to enhancing battery performance, tailored catalyst materials provide a greener, more sustainable alternative to conventional platinum-based catalysts, which in turn lowers manufacturing costs.

Table 7. Performance characteristics of Al–air battery

Parameter	Typical Value for Al–air Battery	Remarks
Specific Energy	1,300 – 2,700 Wh/kg (theoretical max: ~8,100 Wh/kg for Al metal)	Among the highest for metal–air batteries; only a fraction is realized practically.
Specific Power	10 – 200 W/kg	Limited by oxygen reduction kinetics and mass transport at the cathode.
Energy Efficiency	40 % – 55 %	Low due to side reactions (e.g., hydrogen evolution), internal resistance, and sluggish ORR.
Type	Generally non-rechargeable	Commercial Al–air batteries are primary cells (single-use); rechargeable types under research.
Cycle Life	Up to 10–50 cycles (lab scale, with aluminum regeneration)	Rechargeability is difficult due to passivation and complex anode chemistry.

New designs for Al-air batteries have emerged as a result of technological advancements, with the goal of making them more functional, efficient, and versatile. One example is the recent rise of printed Al-air

batteries on paper substrates. These batteries are perfect for printed electronics, such as flexible devices and sensors, since they are disposable, inexpensive, and easy to produce. For one-time use only, these batteries are great for things like medical diagnostic equipment and emergency power sources due to their high specific capacity (Wang *et al.* 2020*;* Wang *et al.* 2019d*)*. Furthermore, Al-air batteries based on polymer alkaline gel electrolytes have been developed to improve operating stability and reduce leakage, making them a safer option for consumer devices. Flexible and portable Al-air batteries that meet the critical requirements of wearable electronics—a high energy density, mechanical durability, and extended operating lifespan—have been developed with the incorporation of electrospun porous carbon nanofibers and electrospun agarose gel electrolytes (Wang *et al.* 2020; Zhang *et al.* 2013*)*.

There are still a lot of obstacles to overcome before Al-air batteries can be commercialized, even with current improvements. One major issue is the deterioration of the aluminum anode, which causes the battery to self-discharge and have a shorter lifetime because passivation layers accumulate and impede ion movement. The use of corrosion-resistant coatings and passivation inhibitors have been suggested as potential solutions to this problem, which might prolong the anodic reactivity of the material (Ma *et al.* 2018; Wang *et al.* 2019e; Liu *et al.* 2021c). There is hope that dual-electrolyte systems and high-strength gel electrolytes may improve electrochemical performance and long-term stability by minimizing self-corrosion (Liu *et al.* 2021b; Sun *et al.* 2020b). Although the components of Al-air batteries are cheap, developing efficient manufacturing procedures that strike a compromise between cost, performance, and environmental sustainability is necessary for large-scale production (Xi *et al.* 2023).

Recent advancements in Al-air battery research underscore the importance of optimizing electrochemical performance (Table 8) through a combination of improved anode compositions, controlled mechanical deformation, and carefully tailored electrolytes. The integration of innovative ORR catalysts, such as defect-engineered MnO_2, and strategic alloying with elements like magnesium, tin, indium, and manganese has demonstrated significant potential in enhancing battery performance. As research progresses, further improvements in electrolyte formulations, anode stabilization strategies, and cathode designs will be essential for making Al-air batteries a viable alternative for various applications, including portable electronics, electric vehicles, and renewable energy storage.

Table 8. Aluminum air battery's electrochemical performance

Anode	Electrolyte	Cathode	Peak power Density	Open Circuit Voltage	Specific discharge Capacity/Energy Density	References
Aluminum foil	KOH	MnO@N/VC_2 Catalyst MnO/N-Doped Carbon black-CNT	44.5 mW / cm^2 @ 60 mA / cm^2	-	1099 mAh/g @ 5mA/cm^2	(Zhang *et al.* 2021a).
Aluminum foil	KOH	Pd/C on Graphite Foil	-	-	2750 Ah/Kg	(Xiao *et al.* 2021).
Aluminium foil	KOH+ZnO+Na2Sn O_3+ In $(OH)_3$+PAA	Fe_3C@N-CFs	41.5 mW/Cm^2	1.8V	1287.3 mAh/g	(Xiao *et al.* 2021).
Aluminum foil	KOH	Pd/C on Graphite Foil	-	-	2750 Ah/Kg	(Xiao *et al.* 2021).
Aluminum foil	Ethanol Gel Electrolyte was prepared using PEO + KOH as the Alkaline source.	Carbon Paper	4mWcm^{-2}	1.72V	2118 mAh/g	(Sun *et al.* 2021b).
Aluminum foil	Sodium Polyacrylate Powder with Sodium Hydroxide	Carbon Paper Cathode	3.8 mW/cm	1.5V	900.8 mAh/g.	(Tong *et al.* 2024).
Aluminum alloy foil (Al - 1Mg -0.1Sn)	NaOH	Manganese Dioxide / Carbon Black	137 mW / cm^2 @ 3 mA / cm^2	-	34.5mAh/cm @ 1 mA/cm^2	(Tong *et al.* 2024).
Aluminum Plate	KOH	MnO_2/Carbon black	-	-	38 mAh/cm @ 0.8 mA/cm^2	(Wang *et al.* 2024b).
Aluminium	EMImCl & $AlCl_3$	Air	-	0.6-0.8 V	-	(Wang *et al.* 2024a).
Al	Polyacrylic Acid (PAA)-based	Air	91.13 mW/cm	-	1166 mAh/g / 1230 mWh/g	(Wang *et al.* 2025).

	Alkaline gel					
Aluminium Spring	KOH+ZnO+$NaSnO_3$+PVA+PEO	Ag/CNT	1.5 mW/Cm^2	1.7 V	935 mAh/g	(Wang *et al.* 2021).
Aluminum foil	KOH and ZnO Aqueous Solution	Activated Carbon+Ether black + MnO_2 + La_2O_3 + SrO + PVDF	25 wt% - 101.14±2.8mW 31wt% - 104±2.9mW	-	25 Wt% KOH - 2343 mAh/g and with 31 Wt% KOH - 2480 mAh/g	(Xiao *et al.* 2023).
Aluminum	NaOH and KOH on H_2SO_4	MnO_2 Catalyst Coated with Activated Carbon	100 to 300 mW/cm^2	2.2 V	1390.92 mAh/	(Xu *et al.* 2024).
Aluminum Plate	Ethylene Glycol and Ethanol with 3 M KOH, MnO_2/C Catalyst	Air	3.75mW/cm^2	-	2,100 mAh/gAl	(Yan *et al.* 2021).
Aluminum plate	Methanol + 3 M KOH, MnO_2/C Catalyst	Air	7.5 mW/cm^2	-	2328 mAh/gAl	(Ye *et al.* 2020).
Aluminum plate	Methanol with 3 M KOH, Pt/C Catalyst	Air	28 mW/cm^2	-	1810 mAh/gAl	(Zhang *et al.* 2024).
Aluminum plate	Solid state ($AlCl_3$, Urea, Carboxymethyl Cellulose, glycerin), TiN catalyst	Air	NA	-	35.8 mAh/gAl	(Zhang *et al.* 2021b).
Aluminum	NaOH/KOH/NaCl	Active Carbon	0.57/5.37/0.65	1.28/0.7/ 1.23	-	(Zhang *et al.* 2024).
Aluminum plate	5 M NaOH Aqueous Solution with 25 m M Thiourea.	Air	NA mW/cm^2	-	1282 mAh/gAl	(Zhang *et al.* 2024).
Aluminum plate	Gel Polymer Electrolyte + NaOH, Ag/C Catalyst.	Air	3.8mW/cm^2.	-	900.8 mAh/gAl	(Zhang *et al.* 2023).
Aluminum metal	1:1.5 [EmIm]Cl - $AlCl_3$	Porous Carbon Air	-	-	6800	(Zuo *et al.* 2019).
Pure Aluminum	Single Electrolyte - PVA-HCl	Pt/Active carbon Catalyst with Polyvinylidene Fluoride in the ratio of 10:1 and 1 cm^3 of solvent (1-methyl-2-pyrrolidinone) per 220 mg of solid mixture	-	1.66	-	(Zuo *et al.* 2022).
Disposable soft drink cans	Arabic Gum and NaOH	Carbon cathode	-	-	0.437 mAh	(Shah *et al.* 2021).
Aluminum	Vanadate and Nanoclay in KOH	Air	3.0 mW	v	8.78 mA/cm^2	(Zuo *et al.* 2019).
Aluminum	NaOH/KOH	Carbon/Carbon with copper/Carbon with Steel mesh/Silver Epoxy with Steel Mesh / Silver Epoxy with Steel Mesh and Carbon.	Maximum current = 17.4 mA Power= 3.0 mW	-	-	(Maárif *et al.* 2021).
Aluminum	5 M NaCl solution	Air	43.88 mW/Cm	1.15V	-	(Phusittananan *et al.* 2020).
Aluminum plate	4 M NaOH aqueous solution, CoO catalyst	Air	48 mW/cm^2	-	770.34 mAh/gAl	(Phusittananan *et al.* 2020).
Aluminum	5 M Hydrochloric acid + PVA hydrogel and Xanthan based hydrogel	Air	-	1.47 V	-	(Teabnamang *et al.* 2020).
Aluminum	5 M Hydrochloric	Air	-	> 2.2 V	5 mAh/cm^2	(Liu *et al.*

	acid + PVA Saline Hydrogel/XaKC					2014).
Aluminum	12 wt% Sodium Chloride + PVA/PEO/MBA gel electrolyte	Air	44.5 mW/cm^2	1.5 - 1.6 V	1099 mAh/g at 5 mA/cm^2	(Ryohei *et al.* 2019).
Aluminum	2 M Potassium Hydroxide + 4 wt% ZnO + PVA hydrogel	Air	-	2.15V	38 mAh at 0.8 mA/cm^2	(Zohreh *et al.* 2017).
Aluminum foil	PVA-LiCl-PEO	MnO_2-CB-PVDF @ Porous Membrane	3.31 mW/cm^2	-	-	(Mori *et al.* 2019).
Aluminum foil	PVA-KOH	p-CD/Graphene @ Carbon cloth	-	1.56 V	-	(Welch *et al.* 2020).
Aluminum foil	PVA-PEO-KOH-Na_2SnO_3-Casein	MnO_2-N/S Graphene@ Microporous membrane	2.01mW/cm^2	-	1630.1 mWh/gAl	(Welch *et al.* 2020).
Aluminum foil	KOH-Na_2SnO_3-ZnO-In $(OH)_3$	Fe-SA-NV@CC	3.94mW/cm^2	2.10 V	-	(Gaele *et al.* 2021).
Aluminum foil	KOH-ZnO-PAA	Electrospun Fibers @Nickel foam	75.5 mW/cm^2	-	-	(Harchegani *et al.* 2020).
Al foil	PBSE	Carbon Paper	3 mW/cm^2	1.5 V	900.8 mAh/g	(Huang *et al.* 2022).
Aluminum	EMlMCl: $AlCl_3$ (1:1.5)	Sulfur -Carbon Composite	-	0.6 V	1300 mAh/g @ 50 mA/g	(Maria *et al.* 2022).
Aluminum	Aluminum / 1 - Butyl - 1-Methylpyrrolidinium Trifluoromethanesulfonate : $AlCl_3$ 1:1.3	S @ CMK - 3 Cathode prepared through a melt - diffusion	-	0.6 V	1500 mAh/g @ 251mA/g	(Gaele *et al.* 2021).
Aluminum	EMlMCl: $AlCl_3$ (1:1.5)	S @ CMK - 3	-	0.6 V	2000 mAh/g @ 100 mA/g	(Shihao *et al.* 2022).
Aluminum	EMlMCl: $AlCl_3$ (1:1.3)	S@CNF paper	-	0.8 V	1250 mAh/g @ 83.75 mA/g	(Tasirin *et al.* 2021).
Aluminum foil	Sodium Hydroxide - SPA -Paper	Carbon paper	6.4 mW/cm^2	5.6 V (4 Cell in series)	-	(Tasirin *et al.* 2021).
Aluminum	Potassium ferricyanide and KCl	Three - layer BP (60 µm thickness)	1. 4.7 mW/cm^2	0.6V (Stable voltage for more than half a day)	-	(Li *et al.* 2021).
Aluminum foil	PVA-NaCl-glycerol	Carbon paper	37.8 mW/cm^2 (8 Single cells)	0.78V	-	(Wang *et al.* 2020).
Aluminum metal	NaOH	Carbon Fiber Paper supported Ag Catalyst	109.5 mW/cm	1.5V is 40 (mA/cm)	-	(Ziyi *et al.* 2020).
Aluminum metal	KOH	$LiMnO_2O_4$/N-rGO/CFP	12 mW/cm	1.5V	-	(Ying *et al.* 2020).
Aluminum metal	KOH	N-rGO/CFP	7 mW/cm	1.5V	-	(Longsheng *et al.* 2021).
Aluminum metal	3M Potassium Hydroxide and Methonal + Alkali Anion exchange membrane + 3M	60% Pt/C	28 mW/cm	1.5V	-	(Yifei *et al.* 2019).

	KOH/H_2O					
Aluminum metal	NaOH	Ag Powder - Nickel mesh	40 mW/cm	1.5V	-	(Yuxin *et al.* 2022).
Aluminum plate	Gel Polymer electrolyte (2 M KOH), Pt/C Catalyst.	Air	NA mW/cm^2	-	239 mAh/gAl	(Yuxin *et al.* 2022).
Spring like Al substrate	Gel	Carbon-Nanotube (CNT)/Silver -Nanoparticle Hybrid Sheet	-	-	1168 Wh/Kg.	(Yuxin *et al.* 2022).
Aluminum metal	KOH+Na_2SnO_3, $In(OH)_3$ and ZnO	Co_3O_4/N-Doped Ketjenblack/Nickel Foam	30 mW/cm	1.5V	-	(Gao *et al.* 2016).
Aluminum Plate	KOH	Potassium Permanganate / Acetylene Black 50	1.2 mW / cm^2	-	-	(Yang *et al.* 2018).
Aluminum spring	PVA-PEO-KOH-ZnO-Na_2SnO_3	Ag@CNT sheet	1.33 mW / cm^2	1.7 V	1168 Wh/Kg	(Yang *et al.* 2018).
Aluminum Mesh	KOH	La_2O_3 - SrO - MnO_2 / Activated Carbon - Ether Black	91 mW/cm^2 @ 116 mA/ cm^2	-	166 mAh / g @52 mA / cm^2	(Yoo *et al.* 2018).
Aluminum Spring	KOH	Cathode:Ag nanoparticles/Carbon nanotubes	-	-	1230 Wh / Kg @ 0.5 mA / cm^2 / 935 mAh / g @ 0.5 mA/cm^2	(Yu *et al.* 2017).
Al	LiCl solution + Tetra-Methyl Ethylenediamine	MnO_2/Carbon black	3.3 mW / cm^2 @ 12 mA / cm^2	-	735.2 mAh / g @ 0.5mA / cm^2	(Yosuke *et al.* 2021).
House-hold Al foil	NaCl	Co_3O_4 Nanoparticles on Carbon Fibers	-	-	20 mAh / g @ 1.3 mA / cm^2	(Yifan *et al.* 2021).
Aluminum	KOH Electrolyte was Absorbed by Polpropylene Pad	Activated Carbon and Manganese Oxide (MnO_2) on the Graphite	-	-	1390.92 mAh /g	(Yifan *et al.* 2021).
Metal Al disc	HCl	Pt on Activated Carbon	15 mW/cm^2 @ 30 mA / cm^2	-	2167 mAh / g @ 10 mA / cm^2 1430 Wh / Kg 10 mA / cm^2	(Qingshusi *et al.* 2017).
Metal Al disc	KCl	Pt on Activated Carbon	3.2 mW / cm^2 @ 17 mA / cm^2	-	21 mAh / cm^2 @ 3mA / cm^2 ; @7 h discharge duration	(Liu *et al.* 2015).
Aluminium Plate	KOH+PVA/PAA	$KMnO_4$/C	1.2 mW/Cm^2	1.5V	-	(Liu *et al.* 2016).
Aluminium Mesh	KOH/ZnO+PAA	La_2O_3+SrO+MnO_2	91.1mW/Cm^2	1.3-1.35 V	1166 mAh/g	(Wang *et al.* 2015).
Al Mesh	KOH	La_2O_3-SrO-MnO_2 / Activated Carbon - Acetylene Black	-	-	40 mAh / g @ 1 mA/g	(Wang *et al.* 2015).
Al plate	KOH	MnO_2 dispersed on activated Carbon	69 mW/cm^2	-	25 mAh/cm @ 10 mA/cm^2	(Wang *et al.* 2015).
Metal Al disc	HCl	Pt on Activated Carbon	-	-	0.05 mAh/g @ 0.1 mA/cm^2	(Fan *et al.* 2015).
Metal Al disc	HCl (Anolyte), NaCl (Catholyte)	Pt on Activated Carbon	-	-	10 mAh/g @ 0.1 mA/cm^2	(Liu *et al.* 2016).
Al foil	KOH	Mn_3O_4 / Carbon Black	3.8 mW/cm^2 @ 3 mA/cm^2	-	288.5 mAh/g @ 1 mA/cm^2	(Zhang *et al.* 2014).
Al foil	NaOH	N-Doped Graphene (Ni@N-G)	27 mW/cm^2 @ 25 mA/cm^2	-	2148.5 mAh/g @ 60 mA/cm^2 / 2766.9 Wh/Kg @ 3 mA/cm^2	(Chen *et al.* 2021a).
Aluminium foil	K- Carrageenan+KOH	Pt/C	-	1.7V	400 mAh/g	(Chen *et al.* 2021a).
Metal Al disc	NaCl	Pt on Activated Carbon	3.3 mW/cm^2 @	-	21 mAh / cm^2 @	(Gaele *et al.*

			14 mA/cm^2		3mA / cm$^{2;}$ @7 h discharge duration	2022).
Aluminium foil	NaOH+ZnO+Na_2SnO_3+Agarose gel	N-Doped Graphene	26.9 mW/Cm^2	1.4V	2148.5 mAh/g	(Li *et al.* 2018).
Al/Al – Alloy (Ca, In, Zn, Sn, Mn, Bi, Sb)	NaOH	Air Cathode (Active Carbon, Catalyst and PTFE)	-	1.45 V	-	(Liu *et al.* 2018).
Aluminium Plate	KOH+ Hydroponics gel	MnOx/C	5.5 mW/Cm^2	1.94V	105 mAh/g	(Liu *et al.* 2018).
Commercial Al Alloy	KOH+PVA/PAA	MnO_2/C	-	-	426 mAh/g	(Pino *et al.* 2015).
Aluminium Plate	KOH+PVA	Co-N/CNS	41.5 mW/Cm^2	1.4V	-	(Shen *et al.* 2018).
Aluminum foil	KOH	Carbon Fiber Cloth	-	1.1 V	375 mAh/g for 30 mA	(Chen *et al.* 2015).
Al	KOH and H_2SO_4	Carbon Paper with Pt/C	175 mW/cm^2	600mV	-	(Chen *et al.* 2015).
Aluminum	Acetamide: $AlCl_3$ (1:1.5)	S@Multi-walled Carbon Nanotubes (CNT)	-	0.5 V	2100 mAh/g @ 50 mA/g	(John *et al.* 2020).

3. CHALLENGES

Metal-air batteries, including aluminum-air (Al–Air) batteries, offer high theoretical energy density, lightweight design, and cost-effectiveness, making them attractive for energy storage applications. However, their commercial viability is limited by several critical challenges. In general metal–air systems, issues such as instability of the air electrode due to poor catalytic activity for oxygen reduction and evolution reactions (ORR/OER), carbon corrosion, and electrolyte management problems—especially with water-based electrolytes prone to evaporation and CO_2 contamination—significantly reduce performance and lifespan. These batteries also suffer from metal anode degradation through corrosion or passivation, difficulty in oxygen management due to contamination from ambient air, and complex mechanical structures that make scalability a challenge. Furthermore, many metal–air batteries are non-rechargeable, and developing efficient rechargeable variants remains a major research focus. Specifically, Al–Air batteries face additional obstacles such as anode passivation from the formation of aluminum hydroxide layers, which hinder further reactions and reduce efficiency. Hydrogen evolution during discharge presents safety risks and material loss, while aluminum's high reactivity with aqueous electrolytes accelerates corrosion and self-discharge. Although aluminum alloys (e.g., Al–Ga, Al–Sn) can improve anode performance, they raise manufacturing costs. Moreover, the cathode's catalytic inefficiency for ORR/OER and its degradation over time, combined with environmental sensitivity to humidity, temperature, and CO_2, further complicate their practical use. These challenges must be addressed to unlock the full potential of metal–air and Al–Air battery technologies.

4. CONCLUSION

Electric vehicles and handheld gadgets are only two of many possible applications for metal-air batteries (MABs), a kind of energy storage technology. The urgent need for efficient, environmentally friendly, and economically viable electricity solutions is shown by their increasing popularity. Distinct from the other MAB types, zinc-air, sodium-air, magnesium-air, lithium-air, and aluminum-air batteries are rechargeable and may be deployed on a wide scale. The metal anode, electrolyte composition, and air cathode design determine the electrochemical properties of these various battery types. The tremendous potential energy density and practicality of aluminum-air batteries have piqued the curiosity of many. Research on these batteries explores various cathode and electrolyte materials to improve critical electrochemical characteristics such as open-circuit voltage, peak power density, specific discharge capacity, and kinetic energy density. Anode corrosion, electrolyte stability, and ORR efficiency are some of the optimization targets aimed at improving performance and increasing the commercialization of metal-air battery technology.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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