Review Article

Journal of Environmental Nanotechnology

Air-powered Innovation: Exploring the Future of Aluminium-Air Batteries

A. Nagamani Prabu[1*], L. Yogapriya[2], K. Balachander[3] and K. Somasundaram[4]

[1]Center for Energy and Nano Research, Department of Physics, Karpagam Academy of Higher Education, Coimbatore, TN, India
[2]Department of Electronics and Communication Engineering, Hindusthan Institute of Technology, Othakkalmandapam, Coimbatore, TN, India
[3]Department of Electrical and Electronics Engineering, Sri Ramakrishna Engineering College, Vattamalipalayam, Coimbatore, TN, India
[4]PG and Research Department of Physics, Nallamuthu Gounder Mahalingam College, Pollachi, TN, India
Received: 17.07.2025 Accepted: 04.09.2025 Published: 30.09.2025
*prabhu.spectra@gmail.com

ABSTRACT

This review examines the development of aluminium-air (Al-Air) batteries, a promising alternative to traditional lithium-ion batteries, particularly in sustainable energy storage applications. Al-Air batteries offer significant advantages, including high energy density, low cost, and environmental friendliness, making them ideal for use in electric vehicles, grid infrastructure, and aerospace. The use of abundant and inexpensive aluminium as the anode further reduces production costs, while the eco-friendly nature of these batteries positions them as a greener alternative. However, despite their potential, Al-Air batteries face several challenges that hinder their commercial adoption. Anode corrosion, electrolyte degradation, and limited rechargeability are the primary obstacles. The aluminium anode degrades over time, reducing battery lifespan, and the electrolyte suffers from performance degradation with use. Additionally, the limited rechargeability of Al-Air batteries prevents them from being widely used in applications requiring frequent cycling, such as electric vehicles. Recent advancements in addressing these challenges have been made, including the development of hybrid systems, protective coatings for the anode, and improved electrolytes. Additionally, research into mechanical recharge solutions and enhancements to battery life holds promise for improving the practicality of Al-Air batteries. These advancements could lead to better integration with renewable energy systems and broader commercial adoption in the future.

Keywords: Al–air battery; Oxygen reduction reaction; Aluminium anode corrosion; Ionic liquid electrolyte; Mechanical recharge; Hybrid storage systems.

1. INTRODUCTION

With the increasing global demand for renewable energy, the need for efficient and sustainable energy storage solutions has never been more urgent. Traditional energy storage systems, such as lithium-ion batteries, are facing challenges due to the limited availability of critical raw materials, high production costs, and environmental concerns (Chen *et al.* 2021; Liu *et al.* 2021). Aluminium-air (Al-Air) batteries offer a promising alternative due to their high energy density, low cost, and the abundance of aluminium. These batteries operate by utilizing aluminium as the anode, with oxygen from the air acting as the cathode reactant (Zhao *et al.* 2023). The primary advantage of Al-Air batteries lies in their ability to achieve higher energy densities than lithium-ion batteries, making them ideal for applications requiring long-duration power supply, such as electric vehicles (EVs) and large-scale energy storage systems (Yang *et al.* 2023). Aluminium is the third most abundant element on Earth and is readily recyclable, which adds to the environmental benefits of Al-Air systems (Zou *et al.* 2023). However, despite these advantages, the widespread commercialization of Al-Air batteries is hindered by several technical challenges, including the degradation of the aluminium anode, instability of the electrolyte, and the fact that these batteries are non-rechargeable (Liu *et al.* 2021; Zou *et al.* 2023). Traditional recharging methods used in lithium-ion batteries are not applicable to Al-Air systems, as the aluminium anode must be replaced once consumed. As a result, significant research is focused on developing hybrid systems, advanced coatings, and new electrolytes to improve the rechargeability and performance of Al-Air batteries (Li *et al.* 2023)

1.1 Aluminium-air Batteries as a Solution

The Al-air battery system functions as a main metal-air battery because it utilizes aluminum anodes, together with oxygen from air, as cathode reactants, integrated with aqueous or ionic liquid electrolytes. Al-air battery recharging operates by extracting oxygen from the air atmosphere, thus eliminating both weight burdens and material costs (Zou *et al.* 2023). The operational mechanism enables Al-air batteries to be the most energy-efficient and environmentally friendly battery technology currently available.

1.1.1 Advantages of Aluminium-air Batteries

Beneficial Al-air batteries possess an energy capacity of 8.1 kWh/kg, surpassing lithium-ion batteries at 0.25 kWh/kg (Li *et al.* 2023). Al-air batteries demonstrate high energy-density characteristics that make them ideal for extended power supply demands, thus they find applications in electric vehicles and remote power systems. The availability of aluminium as a crustal element enhances its status as the third most abundant element on Earth, in addition to the affordability of Al-air batteries compared to lithium-ion technologies (Yang *et al.* 2022). The combination of low production expenses makes Al-Air technology suitable for large-scale energy storage facilities because the aluminium hydroxide byproduct serves as a recyclable material for the aluminum industry (Liu *et al.* 2021). Weight optimization in Al-air batteries remains outstanding because these devices lack heavy cathode materials, which makes them ideal for transportation and aerospace applications, according to Zhao *et al.* (2023).

The safety characteristics of Al-air batteries, including their non-flammable properties and low thermal runaway potential, make them less prone to explosion and fire hazards compared to lithium-ion batteries (Chen *et al.* 2021).

1.2 Challenges Limiting Commercialization

Several technological obstacles prevent the mass production of Al-Air batteries in commercial markets. The interaction between the anode material, aluminium, and alkaline electrolytes prompts both self-corrosive damage and increased energy consumption over time (Liu *et al.* 2021). The main limitation of Al-Air batteries is their one-time usage, as approaches to reverse the aluminum oxidation process have not been yet successfully developed. The present research concentrates on establishing hybrid Al-air and mechanically rechargeable battery systems (Zou *et al.* 2023). The development of ionic liquid-based and solid-state electrolytes became necessary to extend service life and improve performance, as electrolytes in traditional aqueous solutions deteriorate over time (Li *et al.* 2023).

The battery needs a high level of oxygen diffusion efficiency to maintain continuous operation through cathode chamber oxygen access. To achieve maximum performance, better catalyst design, along with optimized air electrode structures, needs to be developed (Yang *et al.* 2021b).

1.3 Current Research and Development Efforts

Research teams have developed various innovative methods to solve the current battery-related problems Advanced protective coatings combined with inhibitors have been developed to achieve two key objectives that extend the lifetime of aluminium anodes (Chen *et al.* 2021).

Ionic liquids in conjunction with neutral aqueous solutions are evaluated as potential electrolyte additives to enhance electrolyte stability while reducing anode degradation, as reported by Li *et al.* (2023). Research has identified potential methods to improve rechargeability and efficiency by integrating hybrid aluminium-based batteries, which combine Al-air technology with connections to aluminium-ion and aluminium-sulfur secondary battery systems (Yang *et al.* 2021a). Researchers utilize manganese dioxide and silver and platinum compounds, combined with advanced porous carbon structures, to enhance the efficiency of the oxygen reduction reaction (Zhao *et al.* 2023). The ongoing advancement of air cathodes makes Al-Air batteries a promising next-generation power storage technology. Materials optimization and electrochemical mechanisms of advanced catalysts (MnO_2, Ag, Pt-based materials) will be further explained in the following sections alongside recent technological improvements.

Table 1. Advantages of aluminium-air batteries: high efficiency, low cost, and sustainability

Advantage	Explanation
High Energy Density	Aluminium-air batteries have one of the highest energy densities among battery technologies, up to 8 kWh/kg, making them ideal for long-range use.
Abundant & Low-Cost Material	Aluminium is the third most abundant element on Earth and is significantly cheaper than lithium, reducing overall production costs.
Lightweight	Compared to other metal-air batteries (like zinc-air), aluminium-air systems offer lighter weight, which is beneficial in EVs and portable devices.
Non-Toxic and Safe	Aluminium is non-toxic, non-flammable, and stable under ambient conditions, providing a safer battery chemistry than lithium-ion alternatives.
Recyclability	Spent aluminium can be recycled easily, and the by-products (like aluminium hydroxide) are also non-hazardous, supporting sustainable energy cycles.
Environmentally Friendly	Aluminium-air batteries generate no harmful emissions and have a low environmental impact during both operation and disposal.
Extended Shelf Life	Because they are mechanically recharged (by replacing the aluminum anode), they can be stored for long periods without losing performance.

1.4 Objectives of this Review

The research focuses on examining contemporary research and technological evolution in Aluminium-Air (Al-Air) battery science from 2019 to 2024. The discussion explains Al-Air battery

fundamentals by describing electrochemical processes alongside design concepts and the conversion methods that generate power. The review discusses recent material developments that focus on aluminum anode improvements, together with cathode catalyst advancements and electrolyte formulation advancements, to achieve longer product lifespan and higher efficiency. The evaluation examines the enhancements achieved by overcoming performance-related issues, such as anode corrosion, self-discharge, and electrolyte instability, with a special focus on recent protective coating technologies, hybridization approaches, and additive implementations.

The review proposes future research topics to enhance rechargeability and optimize air electrode structures, as well as studies on integrating Al-Air batteries with other storage systems. This review aims to address the development needs of Al-Air batteries, advancing their commercialization process and supporting sustainable energy storage solutions.

2. WORKING PRINCIPLE OF ALUMINIUM AIR BATTERIES

Aluminium-air (Al-air) batteries operate on an electrochemical reaction between aluminium and oxygen produced from the air, generating electrical energy. With the class of metal-air batteries, these batteries obtain electricity from the oxidation of the anode metal, which releases electrons that enter the external circuit to generate power. Fundamentally, aluminium is oxidized at the anode and oxygen is reduced at the cathode in the presence of an electrolyte (Liu *et al*. 2020). Herein, an aluminium anode is used as the electron donor and undergoes redox reaction when it is immersed in an aqueous or ionic liquid electrolyte. Catalyst promoters enhance reaction kinetics and overall battery efficiency by facilitating the oxygen reduction reaction (ORR) at the cathode (Chen *et al.* 2021). Unlike conventional lithium-ion batteries, heavy cathode materials are not required in the reaction setup for Al-Air batteries, making them very lightweight, as they The weight of the battery depends on the specific design and material configuration, with the aluminium anode being a significant contributor to its overall weight. (Zhao *et al*. 2022). Compared to lithium-ion and other chemistries, the theoretical energy density of this system is one of its key advantages, reaching a value of approximately 8.1 kWh/kg, making Al/Al-Air batteries suitable for high-energy applications, such as electric cars. For example, however, their practical performance is often limited by such problems as anode passivation, electrolyte instability, and low rechargeability (Zou *et al.* 2024). Recent developments in engineering materials, electrolyte formulation, and hybrid battery architecture have focused on overcoming these challenges to enhance efficiency and accelerate the commercialization of vanadium flow batteries.

2.1 Electrochemical Reactions

The overall reaction in an Al-air battery can be expressed as:

Anode Reaction (Oxidation) $Al + 3OH^- \rightarrow Al(OH)_3 + 3e^-$ +2.31 V

Cathode Reaction (Reduction) $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ +0.40 V

Overall Reaction $4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3$ +2.71 V

The generation of electrical energy occurs while aluminum hydroxide is produced simultaneously in these reactions. The hydroxide obtained from this process provides circular functionality, enabling aluminum metal recovery through smelting, as well as applications in cement production and building materials. The ability to recycle aluminum hydroxide enhances the environmental friendliness of Al-Air batteries. The environmental impact from battery disposal becomes lower due to reduced adverse effects. Researchers aim to utilize this byproduct to its maximum potential, establishing Al-Air battery technology in compliance with circular economy principles.

2.2 Role of Electrolytes

Electrolyte selection is the critical factor in determining battery operational specifications and functions. Alkaline solution buffers enable faster ion movement while they harm aluminum anodes by creating oxide layers that cause surface passivation and prevent electrochemical reactions from proceeding. The technical issue reduces the battery's operational duration while decreasing its performance efficiency. According to Liu *et al*. (2021) and Zhao *et al*. (2023), surfactants and inhibitors in electrolytes enhance aluminum utilization in anti-corrosion and application research. Hybrid electrolyte solutions are used to achieve better battery performance while minimizing the presence of battery corrosion (Li *et al.* 2022). The safety benefits of ionic liquid electrolytes align with their ability to create stable and non-flammable chemical systems that slow self-corrosive processes while enhancing battery lifetime. The use of ionic liquids in batteries leads to optimized electrochemical boundaries, minimizing the adverse effects that shorten battery lifespan. Ion performance decreases when the viscosity of the substance becomes elevated, as reported by Chen *et al.* (2021). Solid-state electrolyte performance relies on stopping electrolyte evaporation while protecting CO_2 from environmental contamination, as noted by Kim *et al*. (2020). A room temperature limitation arises from electrolytic materials that exhibit weak conductivity, thereby minimizing the available capacity of the battery (Lee *et al.* 2021). (Chen *et al.* 2023) report that research on polymer-based composite electrolytes produces better ion conductance alongside total stability characteristics. Within the field of electrolyte research, investigators focus on achieving two primary objectives: optimizing battery efficiency and

extending the service lifecycle duration through stability control and reaction management (Zhao *et al.* 2023).

2.3 Oxygen Reduction at the Cathode

The cathode allows oxygen reduction reactions (ORR) operations that determine Al-Air battery efficiency and power output. The battery achieves improved performance due to the combination of platinum with silver and carbon-based materials, which enhances reaction kinetics and improves oxygen diffusion efficiency. Despite its high initial expense, because platinum excels over standard materials (Chen *et al.* 2021). Wang *et al.* (2023) published findings indicating that manganese oxides, together with cobalt-based materials, demonstrated stable performance as catalysts throughout all periods of study. Laboratory studies suggest that carbon-based catalysts become promising and affordable catalysts for the oxygen reduction reaction after incorporating heteroatoms such as nitrogen or sulfur (Zhao *et al.* 2024). Research on optimizing these catalysts, aiming to achieve improved capabilities at a reasonable price for industrial production scale-up is going on.

3. MATERIALS AND DESIGN CONSIDERATIONS

3.1 Anode Material

Anode material selection is crucial in determining the performance, efficiency, and lifespan of an aluminium battery. The conventional process utilizes high-purity aluminum (99.99%), which is advantageous due to its high conductivity and high energy density. Purity contributes to more efficient charge transfer, leading to a higher theoretical capacity. However, this material is prone to autocorrosion due to contact with aqueous electrolytes, particularly under open-circuit or partial-discharge conditions. This self-corrosion generates hydrogen release and passive film buildup on the aluminum surface, both of which cause a substantial decrease in the battery's cycle life and operational stability (Liu *et al.* 2021). To overcome this problem, corrosion inhibitors have been introduced into the electrolyte. These inhibitors encompass organic molecules and metal ions, forming a protective coating on anode surfaces that impede corrosion or reaction. Research carried out a couple of years ago has demonstrated that chemicals such as silicates, phosphates, and organic surface-active agents can also effectively stabilize the anode–electrolyte interface, thereby preventing side reactions and extending battery life (Zhao *et al.* 2023). In addition to modifying the electrolyte, alloying the aluminum anode with other elements has become a new strategy to suppress corrosion and improve performance. Aluminium alloys have been found to exhibit higher corrosion resistance and greater mechanical capacity, including those containing magnesium (Mg), Gallium (Ga), and Zinc (Zn). These alloying elements alter the electrochemical potential of the aluminum, reducing its tendency to oxidize. Among the several, gallium-doped aluminum anodes have shown highly promising performances. Gallium, in addition to improving corrosion resistance by promoting the formation of a stable and gem-like oxide, also enhances the capacity for discharge; moreover, overvoltage discharge occurs during operation. These effects lead to improved battery efficiency, longer cycle life, and better overall performance (Tian *et al.* 2022). Additionally, gallium's potting effect on hydrogen evolution also makes the system safer and more reliable. In general, the substantial R&D of high-end aluminium anode materials, through high-purity refinement, strategic electrolyte, and alloying, continues to be a key emphasis in the advancement of aluminium battery technology. Future research may focus on optimizing this strategy in conjunction, aiming to establish a scalable, cost-effective, and high-performance solution (Zhang *et al.* 2023; Zhao *et al.* 2023).

3.2 Cathode Material

The cathode plays a vital role in aluminium-air batteries by facilitating the oxygen reduction reaction (ORR), which directly influences the overall energy efficiency and power output. The design and composition of cathode materials are therefore critical to improving battery performance, stability, and longevity.

3.2.1 Oxygen Reduction Catalysts

Tales regarding the sluggishness of ORR in aqueous solutions necessitate efficient catalysts for upcoming reaction kinetics and lowering overpotential losses. Transition metal oxides, together with noble metals, serve as regular catalysts. The combination of low price, suitable electroactivity, and environmentally safe operation makes manganese dioxide (MnO_2) one of the most commonly used materials in electrochemistry (Chen *et al*. 2021). Agnite exhibits better ORR catalytic efficiency compared to MnO_2; however, platinum (Pt) maintains its position as the reference catalyst, as it performs exceptionally well for ORR and has high electrical conductivity. The high price, combined with the limited supply of Pt, imposes restrictions on its utilization in commercial applications (Chen *et al*. 2021).

$La_{1-x}Sr_xCoO_3$ and $LaMnO_3$ perovskites succeed as ORR catalyst materials because they exhibit adjustable electronic behavior along with flexible crystal structures and natural oxygen vacancy content for improved reaction performance (Wang *et al.* 2023). The materials enable sustainable, cost-effective operations, allowing for their implementation on a large scale within aluminium-air systems.

3.2.2 Porous Carbon Structures

The physical structure of the cathode also influences the efficiency of oxygen diffusion and electron transport. The microstructure of porous carbon-based materials, including activated carbon, carbon nanotubes, and graphene, is designed to form an extensive surface area and a network of pores, providing oxygen permeability as well as electrolyte contact. The distinctive structure accelerates the reaction and enhances the overall performance of the ORR process (Yang *et al*. 2021a).

A combination of remarkable internal strength, high surface area, and robust mechanical strength, along with electrical conductivity (when using graphene-based cathodes), results in durable, low-resistance cathodes. An extended operational period is allowed for the device due to the material characteristics, which also enable steady voltage patterns across various application scenarios (Yang *et al.* 2021b). Surface functionalization and heteroatom doping enhance the catalytic activity of carbon-based materials because these processes introduce binding sites for oxygen molecules, facilitating electron transfer.

3.2.3 Hybrid Cathode Designs

Researchers have developed hybrid cathode designs as an advanced approach to enhance the electrochemical performance of aluminum-air batteries by integrating high-surface-area carbon materials with nanoparticles of metals and metal oxides that possess catalytic properties. Multiple functions can be achieved through integrated structures that unite carbon materials with metal nanoparticles, thereby addressing issues related to low catalytic activity and metal nanoparticle aggregation. Porous frameworks receive oxygen swiftly because high-surface-area graphenes, aerogels, and activated CNTs perform as dependable electronic conductors. The operational stability duration increases substantially, and current density values rise when carbon matrices integrate nanometal catalysts, such as Pt or Ag, together with transition metal oxides, including Co_3O_4, Fe_3O_4, or NiO (Chen *et al.* 2022). Li *et al.* (2023) developed a cathode system that placed cobalt oxide (Co_3O_4) nanoparticles onto nitrogen-doped graphene material. In this combined system, the carbon matrix, together with Co_3O_4 components, facilitates more efficient catalysis through its ability to enhance oxygen permeability, conductivity, and the availability of catalytically active ORR sites. The doping process of graphene with nitrogen generates changes in its electronic structure, enabling ORR support.

Research by Zhang *et al*. (2021) demonstrated that cathode material performance reached its optimal point when utilizing MnO_2 nanoparticles evenly distributed across the CNT surface. An optimal interconnection between carbon and MnO_2 support optimizes electric flow while preventing MnO_2 structural breakdown and maintaining dispersity throughout extended battery operation cycles. Researchers have introduced MOF-derived catalysts into aluminum-air batteries through an innovative approach in developing their cathode systems. Heating MOFs transforms them into conductive carbon-metal composites with metal nanoparticles homogeneously spread in the carbon network. These components have material properties that comprise controlled porosity and a large surface area, with embedded built-in catalytic properties, making them suitable materials for aluminium-air battery cathodes (Zhao *et al.* 2022). The incorporation of hybrid cathodes results in better mechanical stability, maintaining a stable structure throughout ongoing operations. The carbon framework behaves as a structural defense mechanism under pressure exposure, expanding through volume changes while retaining nanoparticle functionalities to provide continuous catalytic functionality. These coordinated features produce an enhanced product lifecycle, along with sustained oxygen reduction reaction output (Liu *et al.* 2022). Academic research now aims to establish environmentally friendly synthetic processes, along with functional hybrid cathodes that can operate at standard temperatures and pressures. Hybrid cathode materials offer an innovative approach to enhancing the performance output of aluminium-air battery systems. The integration of porous carbon conductive structures with structural advantages and metal or metal oxide nanocomposites provides improved oxygen reduction performance, along with extended service duration, while enhancing total electrochemical characteristics.

3.3 Electrolyte Selection

An aluminium-air battery relies on an electrolyte that permits the transfer of ions while influencing the electrochemical processes that occur at its electrodes. The compound structure of the electrolyte has a substantial impact on both the energy output and the battery stability duration. The selection of proper electrolytes plays a crucial role in both the output energy performance and the system's operational lifespan.

3.3.1 Aqueous Electrolytes (NaOH, KOH)

The most frequent electrolytes for aluminium-air batteries include NaOH and KOH solutions, as they exhibit high ionic mobility and facilitate rapid electrochemical charge transfers. The combination of electrolytes enables efficient reactions between aluminum and oxygen, producing high energy and decreasing the device's resistance.

The primary disadvantage of alkaline electrolytes stems from their propensity to induce rapid anode aluminum corrosion, which occurs spontaneously. Hydrogen gas evolution, along with the loss of active

material, causes a decrease in overall energy efficiency (Tian *et al.* 2022). Surface passivation occurs when aluminium hydroxide forms an insulating layer, which hinders additional electrochemical reactions on the anode. The addition of phosphate-based additives creates protective surface bonds with aluminum anodes, which slows down corrosion rates and strengthens battery operational times (Tian *et al.* 2022). The effectiveness of stabilizing electrode–electrolyte interfaces can be evaluated by both silicates and organic molecules (e.g., benzotriazole) and other inhibitors, as noted by Wang *et al.* (2019).

3.3.2 Neutral Electrolytes (NaCl, $AlCl_3$)

The replacement for alkaline systems in water electrolysis operates through sodium chloride (NaCl) and aluminum chloride ($AlCl_3$) solutions, which offer enhanced stability and performance. The welcome benefit of these electrolytes is their ability to reduce aluminium anode corrosion while extending the useful life of the battery systems. Such electrolytes prevent the formation of gaseous hydrogen products, thereby improving battery safety over extended periods of use. The primary shortcoming of neutral electrolytes is their poor ionic conductivity, which results in reduced power output and slower reaction rates. Researchers have proposed hybrid electrolyte systems to address this issue, as they integrate high-conductivity alkaline electrolytes with stable neutral electrolytes. Research indicates that electrolytes composed of a NaOH and NaCl mixture deliver both acceptable conductivity and minimal corrosion rates (Wang *et al.* 2020). Research analyzes how electrolyte pH affects hybrid systems during performance-oriented stability tests. When electrolytes are maintained at pH values between 8 and 9, degradation of anodes decreases, while conductivity experiences minimal loss, according to Zhang *et al* (2021).

3.3.3 Ionic Liquid Electrolytes

The ionic liquids (IL) function as stable liquid substances above room temperature. The unique zero-vapor-pressure nature of these electrolytes prompts battery researchers to study them for future aluminum-air battery development, as they also present extensive electrochemical stability and corrosion-blocking functionality. Device stability through extended operation becomes possible because ionic liquid electrolytes maintain water retention and stop electrode loss (Zhao *et al.* 2023). The electrolytic systems improve energy efficiency by enabling longer operation times because they block the hydrogen evolution reaction side effect. Small amounts of water or co-solvents added to IL generate quasi-ionic systems that boost electric current transmission and simultaneously protect against corrosion. Deep eutectic solvents (DESs) have also been a choice because these subclass ionic liquids utilize hydrogen bond donors and acceptors, making them economical and environmentally friendly solutions, as noted by Liu *et al.* (2022). The application of ionic liquids for potential use requires rethinking because their manufacturing costs are high, and acquisition is challenging. At the same time, their conductivity levels may fall short of those of aqueous solutions. The academic world works to maximize IL compositions and minimize synthesis costs to achieve business success.

The selection of electrolytes is a crucial factor in developing high-performance aluminum-air batteries. Due to their good conductivity, alkaline electrolytes need protective inhibitors for practical use. Neutral electrolytes provide stability yet result in reduced conductivity. Durable ionic liquids show corrosion resistance, although their manufacturing difficulties remain expensive.

Hybrid electrolytes, combined with additive engineering and ionic liquids, create electrolytes that offer improved performance in terms of conductivity and stability, while reducing production costs. Technological advancements have minimized alloy deployment disparities in aluminium-air batteries, thereby competing with standard energy storage technologies while expanding their potential client base to applications ranging from electric vehicles to grid storage systems.

3.3.3.1 Grid Storage

Aluminium-Air (Al-Air) batteries have significant potential for large-scale energy storage, particularly in applications such as grid storage and backup systems. However, their limited rechargeability and efficiency over prolonged use present challenges for long-term energy storage. To address these limitations, researchers have explored integrating Al-Air batteries with other energy storage technologies, such as supercapacitors and redox flow batteries, to enhance overall system performance.

3.3.3.2 Supercapacitors

These devices store energy electrostatically, providing rapid bursts of power with high efficiency. In Al-Air systems, supercapacitors can complement the battery by handling sudden power demands and providing short-duration power delivery during peak loads. The high-power density of supercapacitors can fill in the gaps during times of rapid discharge from Al-Air batteries, thereby extending their operational life and enhancing their overall efficiency in grid storage applications. When combined, Al-Air batteries can deliver long-duration energy storage, while supercapacitors can quickly supply energy during brief high-demand events.

3.3.3.3 Redox Flow Batteries

Redox flow batteries (RFBs) are a type of rechargeable battery that store energy in liquid

electrolytes, which can be easily scaled for large storage capacities. They offer the benefit of independent scaling of power and energy, which makes them an excellent complement to Al-Air batteries. By integrating Al-Air batteries with RFBs, grid storage systems can take advantage of the long-term energy capacity of Al-Air batteries, while the RFBs manage energy fluctuations and supply power during times when the Al-Air batteries may be inactive or in need of recharging. This hybrid system can provide both sustained and dynamic energy storage, enhancing grid stability and providing a more robust solution for renewable energy storage. By combining these technologies, Al-Air systems can leverage the strengths of supercapacitors' fast response times and redox flow batteries' scalability, leading to more reliable and efficient grid storage solutions.

4. PERFORMANCE AND EFFICIENCY

4.1 Energy Density and Power Output

Aluminium-air batteries are promising storage systems because they offer exceptional theoretical energy density, alongside lightweight components and affordable materials. They exhibit suitable characteristics for electric vehicle applications, aerospace systems, unmanned aerial vehicle usage, and stationary grid energy storage. However, the practical performance of this theoretical potential faces severe electrochemical and structural drawbacks that prevent its practical implementation.

4.1.1 Theoretical Energy Density

According to Zhu *et al.* (2021), laboratory trials demonstrate that Al–air batteries achieve an energy density of 8.1 kWh/kg for aluminium, surpassing the power capabilities of lithium-ion batteries at 0.3–0.7 kWh/kg and zinc-air batteries at 1.0–1.3 kWh/kg. Laboratory tests show that aluminum undergoes redox through a three-electron process ($Al \rightarrow Al^{3+} + 3e^-$), enabling a high theoretical value because each aluminum atom provides three electrons for substantial energy storage per kilogram. The system achieves a lightweight design while maintaining enhanced energy density because it extracts atmospheric oxygen as an oxidant. The theoretical voltage potential of Al–air batteries is 2.7 V; however, operating conditions deviate from this value due to device limitations and uncontrolled side effects.

4.1.2 Practical Energy Density

When used in real-world Al–Air battery systems, the energy density ranges from 1.0 to 1.5 kWh/kg; however, the specific values depend on operational conditions and design specifications (Liu *et al.* 2022). Multiple operational inefficiencies, combined with degradation processes, cause variations in energy density.

The aluminium surface passivates when aluminium hydroxide or alumina layers form, which decreases both electrochemical activity and surface availability.

The chemical activity of aluminium in aqueous solutions produces hydrogen gas and degrades battery materials during open-circuit operation without generating useful power (Tian *et al.* 2022).

Three main factors decrease coulombic efficiency: oxygen crossover, cathode flooding, and degrading conditions of the catalyst layer.

High currents and elevated temperatures lead to electrolyte degradation, affecting conductivity and ionic transport. resulting in numerous changes to conductive capability and ionic transport properties.

The combination of ionic liquid electrolytes and hybrid electrolytes, when used with surface-modified aluminum anodes, yields improved energy density outcomes by mitigating corrosive and passivation effects (Liu *et al.* 2021).

4.1.3 Power Output

Al-Air battery power output is influenced by several factors: operational voltage, current density, electrode design, electrolyte flow, catalytic activity, and air ventilation. Experimental and commercial Al-Air batteries typically output between 1.0 and 1.2 volts per cell (Chen *et al.* 2022), while the theoretical potential is 2.7 volts. Research shows that air cells reach their lower output voltage level through these factors:

- Ohmic resistance within the electrolyte and separators.
- Kinetic overpotentials, especially at the cathode during the oxygen reduction reaction (ORR).

The air electrode encounters diffusion constraints that prevent oxygen from reaching it at a sufficient rate.

The design specifications of cathodes determine the output performance more than any other factor. Scientific data reveal that using MnO_2 and Ag nanoparticles, as well as perovskite catalysts attached to porous carbon materials, improves the ORR speed and prevents drifting discharge potentials. The combination of improved material architecture leads to laboratory-measured current densities reaching between 100–300 mA/cm^2, with maximum power densities of 300 mW/cm^2. Research advancements leading to the commercial deployment of these values demand stability during extended operational periods and multiple discharge cycles.

4.1.4 Other Enhancements Include

- A net improvement in cathode design, achieved through the use of 3D structures, enhances both surface area and airflow capabilities.
- Liquid electrolyte gels reduce contamination while improving electrode connection.

The active airflow system functions to preserve oxygen delivery to the cathode at high discharge rate operations. The commercialization of Al–air batteries remains challenging due to practical barriers, including corrosion and passivation effects, as well as side reactions and voltage losses. Research directions aim to address this problem through collaborative work in electrolyte solution development and materials science, as well as catalyst research and development: future research developments position Al–air batteries as competitive options for lightweight, high-energy applications.

4.2 Comparison with Other Batteries

MeasuringMeasuring the practical use and potential of Al–air batteries requires an investigation of mileage versus other conventional leading battery technologies through analysis of their primary functional metrics, including energy density, rechargeability, operating costs, and longevity. The key benchmarks for battery assessment include the lithium-ion battery (LIB) and the zinc-air battery (Zn–air).

4.2.1 Aluminium-air vs. Lithium-ion Batteries

Al–air batteries offer a theoretical energy density of 8.1 kWh/kg, exceeding the range of lithium-ion batteries, which is between 0.2 and 0.7 kWh/kg (Zhu *et al.* 2021). Al–air cell technology demonstrates superior value for use in electric vehicles and aerospace systems where high energy demands exist during long-range operations.

Technology currently supports lithium-ion batteries due to their capability to recharge, high Coulombic efficiency values exceeding 99%, and long-lasting operation, which enables the success of consumer electronics and the automotive industries. They operate with the benefits of existing geographical networks and rapid recharging features, together with dependable thermal controls. The primary design of Al–air batteries makes them irreversible cells, which present three major drawbacks:

- Irreversible anode degradation
- Electrolyte drying or contamination
- Poor reversibility of the oxygen reduction/evolution reactions (ORR/OER)

The deployment of Al–air batteries for rechargeable systems faces obstacles primarily due to anode degradation and electrolyte circulation issues, yet research continues to develop ways for secondary operation (Liu *et al.* 2022).

4.2.2 Aluminium-air vs. Zinc-air Batteries

Metal-air batteries based on the Zn–Air technology utilize ambient oxygen from the atmosphere as their cathodic constituent, similar to Al–air systems. The energy density of Zn–air batteries ranges from 1.0 to 1.3 kWh/kg, but their recharging potential makes them suitable for flexible and wearable energy devices (Leong *et al.* 2022). Rechargeable management of Zn–Air batteries becomes feasible because zinc anodes demonstrate stability in alkaline conditions along with reversible oxygen electrocatalytic reactions at air cathodes. However, they still face technical challenges such as:

- Cathode degradation over cycles
- Formation of zinc dendrites
- Carbonate precipitation from CO_2 exposure

Al–air cells generate higher theoretical energy than Zn–air cells; however, zinc-based anodes demonstrate superior cycling ability alongside decreased corrosion, presenting better short-term storage possibilities (Gupta *et al.* 2021).

4.2.3 Hybrid Energy Systems: Al–air and Beyond

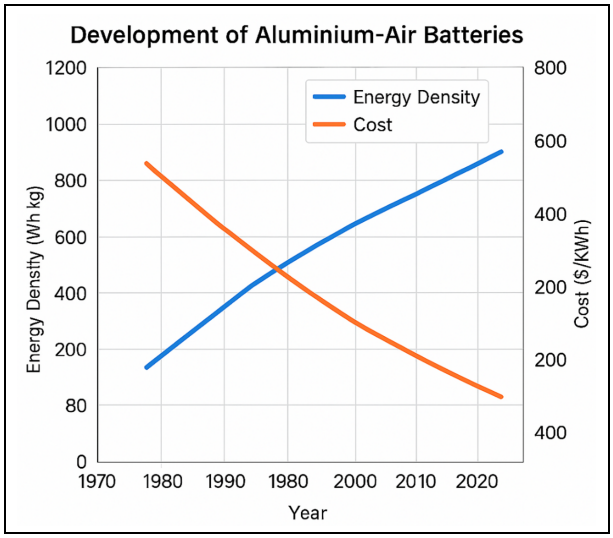


Fig. 1: Development of aluminium-air battery (Chen *et al.* 2022; Li *et al.* 2023; Yang *et al.* 2021b)

Al–air batteries' limitations in rechargeability and other aspects drive researchers to create hybrid systems for power system enhancement. The energy system combines Al–air batteries with supercapacitors, as well as lithium-ion modules or flow batteries, to deliver improved responsiveness, peak power capabilities, and advanced energy management features (Buckingham *et al.* 2021). Supercapacitors added to the system enhance battery performance by handling sudden power demands, resulting in an extended total lifetime. The charge-discharge needs of LIBs and ultracapacitors are supported by Al–air cells, which maintain their role as energy storage elements (Dilshad *et al.* 2025). Air setups powered like fuel cells enable the replacement of their chemical tanks by refilling with aluminum, extending their capability towards high-performance off-grid and extended-range operations. Hybrid energy systems enable the utilization of Al–air battery energy density, along with the rechargeability benefits of other battery technologies. The development of the air depicted is described, with inferences made by various researchers.

The slow self-discharging nature, along with its limited recharging capacity, presents significant barriers to the commercial use of Al-air batteries, despite their promising energy density.

Ongoing investigations into the practicality of Al-air batteries focus on developing better cathode catalysts, electrolytes, and hybrid battery combinations.

Table 2. Comparative overview of aluminium–air, zinc–air, and lithium-ion batteries

Feature	Aluminium–air	Zinc–air	Lithium-ion	Reference
Theoretical Energy Density	8.1 kWh/kg	1.08 kWh/kg	0.7 kWh/kg	(Lv *et al*. 2023; Rani *et al.* 2024; Heo *et al.* 2024)
Practical Energy Density	1.3 kWh/kg	400–450 Wh/kg	~200–250 Wh/kg	(Rani *et al.* 2024; Shumiri *et al.* 2024)
Rechargeability	Limited (Primary Cell)	Moderate (Rechargeable versions emerging)	Excellent	(Rani *et al*. 2024; Shumiri *et al.* 2024; Leong *et al*. 2022)
Cycle Life	Short (one-time use)	100–300 cycles (for rechargeable versions)	1,000–5,000+ cycles	(Shumiri *et al.* 2024; Park *et al.* 2024)
Cost (per kWh)	Low	Moderate	High	(Rani *et al.* 2024; Shumiri *et al.* 2024)
Power Output	Moderate	Low–Moderate	High	(Zhao *et al*. 2020)
Safety	High (non-flammable)	High	Moderate–High	(Rani *et al.* 2024; Shumiri *et al.* 2024)
Commercial Maturity	Emerging	Semi-commercial	Mature	(Rani *et al.* 2024; Shumiri *et al.* 2024)

4.3 Efficiency and Energy Utilization

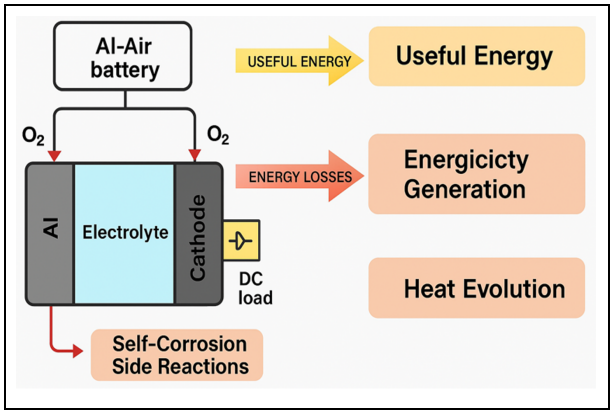


Fig. 2: Inferences by various researchers on the energy conversion diagram

Performance in Al-Air batteries depends on several factors: the reaction speed at the anode and cathode, electrolyte characteristics, and integration methods.

The Coulombic Efficiency of Al-air batteries ranges from 60% to 80%, and its values depend on anode purity and electrolyte component selection (Wang *et al.* 2023). The performance level falls below that of lithium-ion batteries because these devices routinely achieve over 95% effectiveness during their optimal operational state.

Energy Conversion Efficiency: The overall energy conversion efficiency is limited due to the parasitic reactions, such as hydrogen evolution at the anode. Recent research has focused on optimizing electrolyte additives and electrode coatings to enhance energy utilization and reduce energy losses (Zou *et al.* 2024).

Self-discharge Rate: Unlike lithium-ion batteries, which have relatively low self-discharge rates, Al-Air batteries experience significant self-discharge due to continuous corrosion of the aluminium anode in the electrolyte. Studies have shown that self-discharge rates can be reduced by incorporating stabilizing additives, such as gallium or tin, into the aluminum alloy (Liu *et al.* 2022).

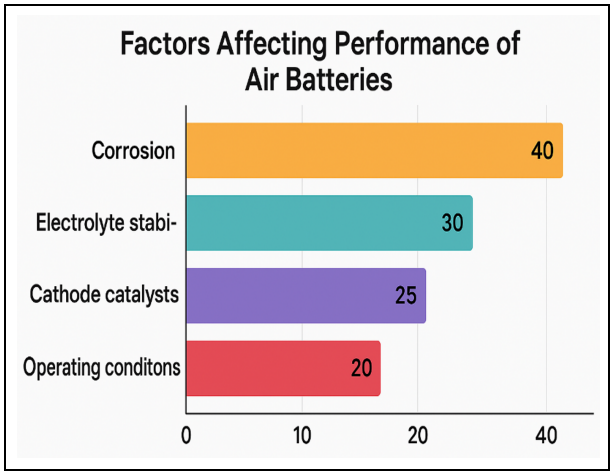


Fig. 3: Factors affecting performance of air battery (Yang *et al.* 2021b; Wang *et al.* 2020; Kumar *et al.* 2023; Lv *et al.* 2023; Zou *et al.* 2024)

4.4 Factors Affecting Performance

Al-air battery operational performance depends on three main factors, which include aluminum anode purity levels, cathode ORR reaction efficiency, and electrolyte stability characteristics. Anode material selection significantly impacts battery efficiency performance, as pure aluminium produces better electrochemistry but exhibits higher susceptibility to passivation (Zhao *et al.* 2023). Researchers added magnesium, zinc, and gallium to aluminum to mitigate various adverse effects while enhancing battery longevity. The selection of cathode catalysts regulates total performance characteristics because platinum and silver catalysts grant impressive ORR efficiency but entail distribution expenses. The combination of manganese oxide catalysts delivers both improved performance and economical price stability (Chen *et al.* 2023). The selection of a suitable electrolyte is crucial because it enhances both electrical performance and mitigates the effects of anode corrosion. Research conducted on hybrid and ionic liquid electrolytes demonstrates their ability to extend battery service life while minimizing self-discharge rates, as reported by Wang *et al.* (2023).

The use of highly pure aluminium anodes enhances electrochemical operations, yet it exposes them to elevated passivation risks. Changing the composition of the battery to include magnesium, along with zinc and gallium, prevents passivation problems, as reported by Zhao *et al.* (2023).

Efficiency in the oxygen reduction reaction at the cathode directly impacts the overall performance. The high cost of platinum and silver catalysts is offset by manganese oxide-based catalyst systems, which combine effective ORR performance with lower prices (Chen *et al.* 2023).

The efficiency of the overall battery depends on electrolytes that possess both high ionic conductivity and minimal corrosion properties. Hybrid and ionic liquid electrolytes are being developed to achieve better performance while reducing anode corrosion (Wang *et al.* 2023).

The resolution of current obstacles enables Al-air batteries to establish themselves as effective storage solutions for diverse applications that primarily depend on cost efficiency and energy density requirements. The data were extracted from Yang *et al*. (2021b), Jiang *et al.* along with Kumar *et al*. (2023), Lv *et al.* (2023), and Zou *et al.* (2024).

5. CHALLENGES AND LIMITATIONS

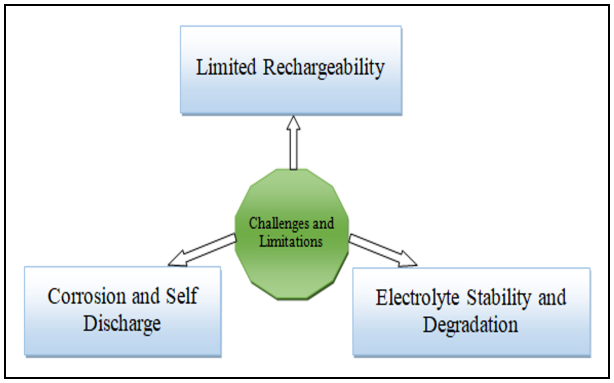


Fig. 4: Challenges and limitations of air battery

Widespread commercial use of aluminium-air (Al-Air) batteries encounters various hurdles that prevent their market-based deployment. The significant barriers to Al-Air battery usage include limited rechargeability, radiation, and corrosion, as well as high cost and low theoretical energy density (Wang *et al.* 2020). The current research investigates new material developments and electrolyte stabilization techniques, combined with innovative cellular engineering, to address existing challenges (Li *et al.* 2023). Self-corrosion in aqueous electrolytes of aluminium shortens battery operational life spans, and electrode passivation occurs due to insoluble aluminium hydroxide precipitates, which reduce efficiency (Chen *et al.* 2022). Current Al-Air battery technology requires the repeated replacement of its anode, as it is non-rechargeable, which creates practical barriers for large-scale applications (Lv *et al.*

2023). A review of the main limitations within Al-Air batteries is followed by a discussion of contemporary research strategies to resolve these issues.

5.1 Corrosion and Self-discharge

Self-discharge and severe corrosion affect Aluminium-air (Al-Air) batteries because of their sustained reaction with aqueous electrolytes. The contact of aluminium with hydroxide ions triggers oxidation, producing hydrogen gas while forming aluminium hydroxide. Active aluminum used for energy generation is significantly reduced because this second reaction consumes active aluminum, thereby decreasing battery lifespan (Yang *et al.* 2021a). The passivation phenomenon results from self-corrosion, which makes the anode oxidation process less efficient (Liu *et al.* 2022). Research works on aluminum-element combinations that include indium, along with gallium and tin were undertaken, because they enhance discharge performance and combat corrosion (Zhang *et al*. 2023). Phosphate-based additives show promise in slowing down the self-discharge rate by creating protective surface coatings on aluminium (Chen *et al.* 2024b). The principal drawback of Al-Air batteries lies in the alarming rate at which the aluminium anode deteriorates due to electrolyte corrosion, as well as self-discharge events. Aluminium interacts with water electrolytes to form hydrogen gas and aluminium hydroxide, thereby shortening the lifespan and decreasing the effectiveness of the battery (Yang *et al.* 2021b). The self-corrosive process decreases the accessible active aluminium while simultaneously reducing battery energy output. Researchers have studied various mitigation strategies by alloying aluminum with indium, gallium, and tin to slow down self-corrosion while enhancing discharge performance, as reported by Liu *et al*. (2022). The electrolyte performance can be improved by adding corrosion inhibitors, along with buffer agents, which help slow down harmful chemical reactions (Chen *et al.* 2023).

5.2 Electrolyte Stability and Degradation

Electrolyte stability stands as a vital variable that determines how well Al-Air batteries function over time. Aluminium hydroxide forms as precipitates on the anode, where they obstruct electrode pores, thus lowering ionic conductivity and causing efficiency degradation (Wang *et al.* 2020). The battery's performance deteriorates over time because electrolyte evaporation, combined with contamination, exacerbates this condition (Buckingham *et al.* 2021). Research teams investigate the use of additives, including citrate and ethylene glycol, to prevent $Al(OH)_3$ precipitation, thereby increasing the solubility of reaction byproducts (Zou *et al.* 2024; Lv *et al*. 2023). It was demonstrated that electrolytes made from both ionic liquids and deep eutectic solvents deliver extended stability, along with corrosion protection to anodes, and enhanced electrochemical battery performance.

For Al-Air batteries, the electrolyte needs stable conditions to maintain both performance levels and product lifetime. $Al(OH)_3$ precipitates commonly form on the electrodes and block pores, reducing battery efficiency due to their impact on ionic conductivity (Wang *et al.* 2020). The formation process of aluminium hydroxide deposits inside the battery cell increases internal electrical resistance while simultaneously decreasing its output power. The use of complexing agents, including citrate and EDTA, represents a solution to prevent aluminium ion precipitation, according to research by Kumar *et al*. (2023). The combination of ionic liquids with hybrid electrolytes shows promise in boosting the endurance and operational excellence of the system (Zou *et al.* 2024).

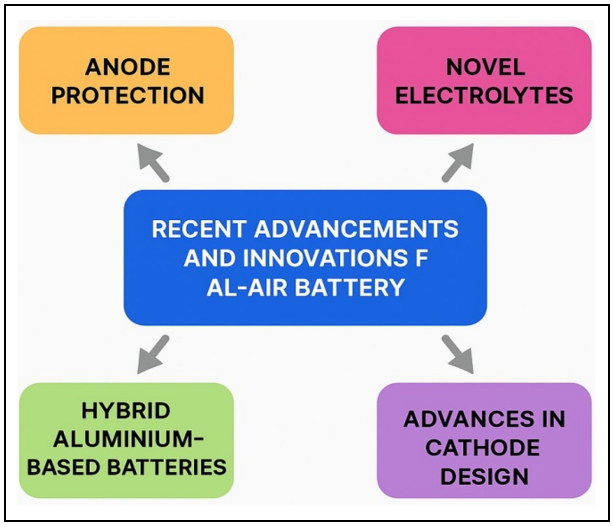


Fig. 5: Recent advancements in Al-air battery tech: anode protection, novel electrolytes, hybrid batteries, and cathode design

5.3 Limited Rechargeability

The aluminum anode in most Al-Air batteries causes the permanent formation of aluminum hydroxide during battery discharge, which renders them incapable of recharge. The technology requires regular human intervention to replace aluminum anodes because these anodes lack rechargeable capabilities, leading to constraints in commercial applications (Zhao *et al.* 2023). Groups of researchers are engaged in the development of aluminum-air batteries through aluminum deposition processes to address the non-rechargeable characteristics of these batteries. The primary hurdle of achieving high coulombic efficiency goals for aluminum redeposition procedures should be overcome (Dilshad *et al.* 2025). Secondary Al-Air batteries require dual-function catalysts that facilitate both oxygen reduction and oxygen evolution, advancing as an essential research approach . The connection of Al-

Air batteries with supercapacitors or redox flow batteries enables researchers to expand their energy storage applications, as noted by Leong *et al*. (2024). The electrochemical recharging system used for lithium-ion batteries operates differently from Al-Air batteries, which lack electrochemical charging functionality. The creation of aluminium hydroxide presents an irreversible problem that prevents the anode from receiving effective aluminium metal deposition (Zhao *et al.* 2023). Manufacturers perform mechanical recharging of aluminium anodes and electrolyte replacement today as the best technique to prolong battery functionality. The development of secondary Al-Air batteries advances through scientific studies on electrochemical aluminium deposition methods, owing to their potential for enhancing rechargeability (Lv *et al.* 2024). Researchers are working to advance bifunctional catalysts for aluminium electrochemical processes, in conjunction with electrolyte formulations, to achieve consistent operation (Dilshad *et al.* 2025).

6. RECENT ADVANCEMENTS AND INNOVATIONS

6.1 Anode Protection

The main drawback of Al-Air battery technology arises from aluminium anode corrosion that results in both self-discharge and efficiency reduction. Researchers have developed surface coatings, alloying procedures, and corrosion inhibitors as anode protection methods to enhance battery performance and prolong lifespan (Chen *et al.* 2021).

Research teams have investigated the use of nanostructured coatings comprising graphene and polyaniline (PANI) and fluoride-based layers to provide physical electrolyte protection for anodes. These coatings produce two beneficial effects for the anode by inhibiting unwanted side reactions and enhancing its electrochemical properties (Zhang *et al.* 2023).

The development of aluminium alloys through the addition of elements Ga, In, Sn, and Bi yields encouraging results, which decrease anode passivation while enhancing discharge performance stability. Evidence shows that anode self-corrosion rates decrease substantially when aluminium contains gallium doping, as this reduces the production of aluminium hydroxide (Wang *et al.* 2024).

Research on the degradation-slowing process has explored organic and inorganic corrosion inhibitors, including phosphate-based compounds and rare-earth metal oxides. A specific category of inhibitors protects aluminium through the creation of protective layers that minimize harmful hydrogen reactions (Li *et al.* 2023).

6.2 Novel Electrolytes

The efficiency and stability of Al-Air batteries depend mainly on the electrolyte formulation selected for the battery. NaOH and KOH solutions represent typical electrolytes in battery systems, as they provide excellent conductivity but accelerate anode degradation. A new generation of electrolyte solutions emerged as researchers sought to develop batteries with enhanced performance and longer service life (Yang *et al.* 2021a).

Ionic Liquids (ILs): Ionic liquids are ideal candidates for next-generation Al-Air batteries because they possess non-flammability, chemical stability, and low volatility characteristics. Electrolytes created from ionic liquids are able to deliver high ionic conductivity while producing lower corrosion rates. The battery performance was enhanced through efficient aluminium dissolution kinetics achieved using imidazolium- and phosphonium-based ILs according to (Lv *et al.* 2023).

Deep eutectic solvents (DESs) represent a recently developed group of environmentally friendly electrolytes that balance IL-like characteristics with cost-effectiveness. The electrolyte solution made from DES allows aluminum to oxidize within a safe environment that limits the formation of $Al(OH)_3$ and other solid precipitates. Scientific studies have shown that batteries function more efficiently when using choline chloride-based deep eutectic solvents, as these systems prevent electrode clogging (Singh *et al.* 2024).

A new generation of battery electrolytes merges two systems to achieve optimized levels of wetness and corrosion protection. The combination of organic solvents with alkaline solutions in hybrid electrolytes enables the maintenance of electrochemical efficiency and slows down self-discharge phenomena (Sheng *et al.* 2024; Chen *et al.* 2024b).

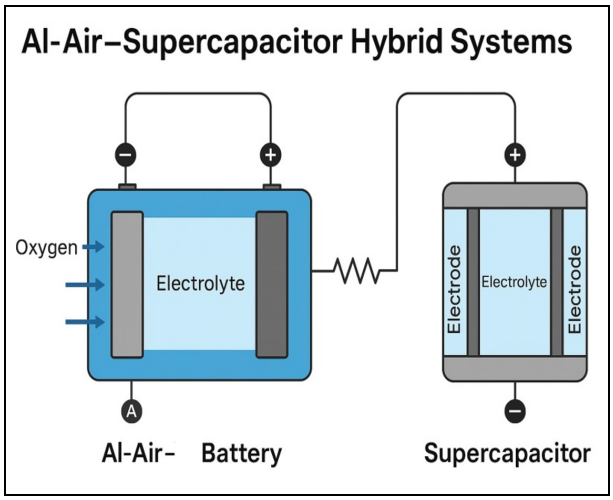


Fig. 6: Schematic of Al-Air-Supercapacitor Hybrid Systems, combining an Al-Air battery with oxygen input and a supercapacitor for enhanced energy storage

6.3 Hybrid Aluminium-based Batteries

Research into Al-Air battery development focuses on integrating aluminium-based energy storage technologies with rechargeable battery systems. The combination technique aims to achieve high Al-Air battery energy density by integrating this system with secondary rechargeable battery principles (Yang *et al.* 2021b).

Researchers have developed Al-air supercapacitor hybrid systems for increased power production and partial battery recharging purposes. This hybrid system exhibits a rapid energy discharge capability, which also provides long-term energy storage advantages (Tong *et al.* 2024).

The proposal to combine Al-Air cells with lithium-ion technology creates Al-Air–Lithium-Ion Hybrid Batteries, which enhance both energy density and cycling capabilities. The Al-Air battery generates primary power in these battery arrangements, though the lithium-ion part ensures better discharge regulation by providing supplementary power (Dilshad *et al.* 2025).

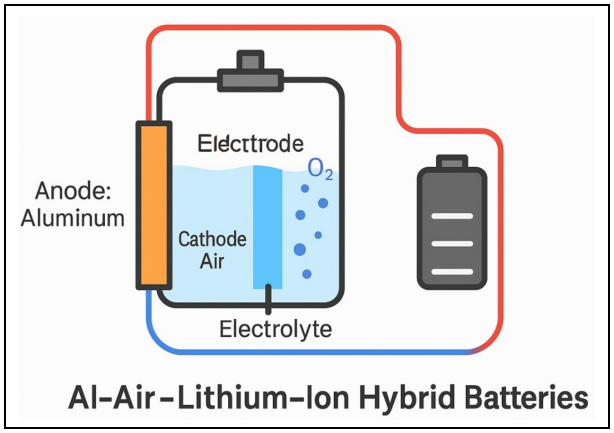


Fig. 7: Diagram of Al-Air-Lithium-Ion Hybrid Batteries, featuring an aluminum anode, air cathode, electrolyte, and integrated lithium-ion battery

A method has been developed to integrate Al-Air batteries using redox flow battery techniques for establishing large-scale energy storage methods. Hybrid systems maintain high energy densities through the continuous circulation of the electrolyte solution, addressing the limitation of rechargeability.

6.4 Advances in Cathode Design

The cathode drives the oxygen reduction reaction (ORR) operation because it directly affects battery efficiency performance. The research community is currently investigating ways to enhance cathode materials to improve both reaction speed and product reliability.

The manufacturing of advanced catalysts containing manganese oxide (MnO_2), platinum (Pt), and silver (Ag) resulted in substantial improvements in ORR efficiency. A recent study has investigated Co-N-C structures as economical alternatives to traditional precious metal catalysts (Zou *et al.* 2024).

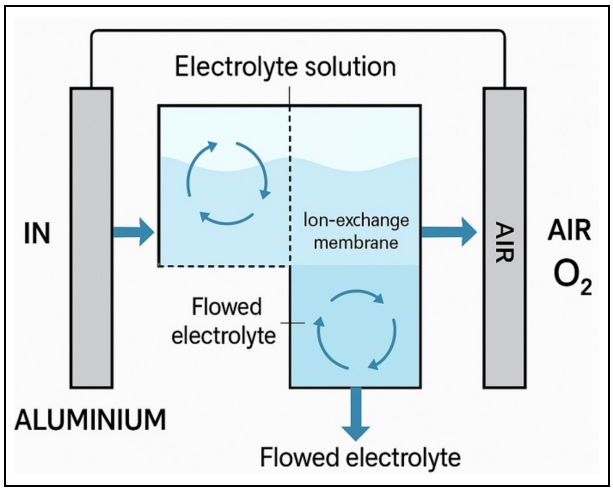


Fig. 8: Flow-assisted aluminium air battery

The adoption of porous carbon materials in cathodes creates extensive surfaces, which help oxygen diffuse more rapidly. Experimental investigations using modified carbon aerogels and graphene-based electrodes have yielded exceptional electrochemical results and enhanced durability, according to Zhao *et al.* (2023). The current developments in Al-Air battery technology focus on key aspects that create conditions for efficient storage solutions with extended life spans and potential market availability.

7. APPLICATIONS AND FUTURE PROSPECTS

7.1 Electric Vehicles (EVs)

Aluminium-air batteries offer significant benefits for electric vehicle (EV) usage, as they deliver high energy density values suitable for automotive applications. Al-Air batteries, in theory, enable typical EVs to travel beyond 1000 km before needing a recharge, according to Liu *et al.* (2021). These batteries present attractive potential as a long-range transportation choice. The implementation of Al-Air batteries in EVs faces substantial obstacles because mechanical recharging requires the replacement of anode aluminum alongside electrolyte replacement (Chen *et al.* 2023). This recharge process proves less convenient than the standard method used for lithium-ion batteries. An efficient refueling station network for aluminium and aluminium recycling systems must be developed before Al-Air batteries can become viable options for commercial EVs (Li *et al.* 2022). Conventional Recharge (in lithium-ion batteries):

Table 3. Comparative overview of aluminium–air, zinc–air, and lithium-ion batteries

S. No.	Battery Type / Title	Key Components	Description	Reference
1	Stable and High-Energy Aqueous Aluminum-based Battery	Anode: Aluminum Cathode: Nickel Hexacyanoferrate (NiFe-PBA) Electrolyte: Poly-Aluminum Ferric Chloride (PAFC)	Demonstrates a high-performance hybrid-ion battery using a strongly hydrolyzed/polymerized aluminum–iron hybrid electrolyte, achieving an energy density of ~42 W h L^{-1}.	(Wang *et al.* 2022)
2	3D-Printed Aluminum Metal–Organic Framework/Sulfur Cathode	Anode: Lithium Cathode: Aluminum Metal–Organic Framework/Sulfur (Al-MOF/S) Electrolyte: Lithium-based	Constructs a hierarchically micro-nanostructured Al-MOF/S cathode using 3D printing technology for lithium–sulfur batteries, enhancing adsorption and redox conversion of polysulfides.	(Xi *et al.* 2023)
3	$Na_3V_2(PO_4)_3$-Decorated $Na_3V_2(PO_4)_2F_3$Cathode for Sodium-ion Batteries	Anode: Sodium Cathode: $Na_3V_2(PO_4)_3$-decorated $Na_3V_2(PO_4)_2F_3$ Electrolyte: Sodium-based	Synthesizes a composite cathode material combining $Na_3V_2(PO_4)_3$ and $Na_3V_2(PO_4)_2F_3$, achieving high-rate capability and cycle stability for sodium-ion batteries.	(Yang *et al.* 2024)
4	Microstructure Tuned $Na_3V_2(PO_4)_3$@C Electrodes for Sodium-ion Batteries	Anode: Sodium Cathode: $Na_3V_2(PO_4)_3$@C Composite Electrolyte: Sodium-based	Prepares $Na_3V_2(PO_4)_3$@C composite electrodes with tuned microstructure, demonstrating ultra-long-life performance in sodium-ion batteries.	(Kate *et al.* 2024)

Table 4. Key developments in aluminium-air battery technology

Advancement	Key Developments	Benefits	Reference
Anode Protection	Nanocoatings (graphene, PANI), Ga/In alloys, corrosion inhibitors	Reduced self-corrosion, extended battery life	(Chen *et al*. 2022; Zhang *et al.* 2023)
Novel Electrolytes	Ionic liquids, deep eutectic solvents, hybrid systems	Increased stability, reduced anode passivation	(Yang *et al.* 2021a; Lv *et al.* 2023)
Hybrid Al-based Batteries	Al-air–Supercapacitor, Al-air–Li-ion, Flow-assisted Al systems	Improved rechargeability, higher power output	(Tong *et al*. 2024 Rajore *et al.* 2024)
Cathode Innovations	Bifunctional catalysts (MnO_2, Ag, Co-N-C), porous carbon structures	Enhanced oxygen reduction, improved ORR kinetics	(Zou *et al.* 2024; Zhao *et al.* 2023)

7.1.1 Conventional Recharge (in Lithium-ion Batteries)

In conventional electric vehicles, lithium-ion batteries are typically recharged by connecting the vehicle to an electric power source, such as a charging station, via an AC or DC electrical connection. During this process, the electric current flows into the battery, reversing the discharge process, and restoring the energy within the battery cells. This method allows for the battery to be recharged multiple times over its lifespan without requiring physical replacement of components (Liu *et al.* 2021). The ability to quickly recharge these batteries and their long cycle life are primary reasons lithium-ion batteries are currently the preferred choice for EVs (Chen *et al.* 2022).

7.1.2 Mechanical Recharge (in Al-air Batteries)

Unlike lithium-ion batteries, Al-Air batteries are non-rechargeable in the traditional sense. Once the aluminium anode is consumed (oxidized), the battery cannot be recharged by simply applying an electrical current. Instead, mechanical recharge refers to a process where the spent aluminium anode is physically replaced with a new one, effectively "recharging" the battery (Zhao *et al.* 2023). This method requires the replacement of the anode, which has been consumed during the discharge process, and possibly the electrolyte, depending on degradation. This makes the Al-Air system different from conventional rechargeable batteries, as it involves physical intervention to replace the consumed components rather than a simple electrical recharge.

For electric vehicles using Al-Air batteries, this means that once the battery's energy is depleted, a physical replacement of the anode would be necessary, similar to refueling a vehicle with a gas tank. While this method provides high energy density, it requires a robust infrastructure for the replacement of spent anodes, which could limit its practicality for everyday EV use (Zou *et al.* 2023).

7.2 Military and Aerospace

Al-Air batteries excel in military and aerospace applications due to their high energy storage capacity and lightweight composition. Researchers have identified the Al-Air battery as an optimal power solution for submarines, as well as UAVs and satellites, because these systems require an extended power supply along with minimal weight (Zhao *et al.* 2023). Al-Air technology exhibits better energy-to-weight performance than lithium-ion and zinc-air batteries, as it is well-suited for high-endurance operations. The low thermal runaway risk of Al-Air batteries confers a superior safety rating, enabling them to operate effectively in harsh environmental conditions (Buckingham *et al.* 2021). Stability improvements to anodes and electrolytes, achieved through recent advancements, have enhanced the reliability of Al-Air batteries when used in challenging military applications (Yang *et al.* 2024).

7.3 Grid Energy Storage

Many researchers have demonstrated that Al-Air batteries present a dynamic potential for meeting renewable energy backup needs, specifically targeting solar and wind applications. Their capacity to store significant amounts of energy affordably makes Al-Air batteries an appealing choice against the currently used lithium-ion and lead-acid batteries for grid-scale storage systems (Tian *et al.* 2022). The implementation of large-scale Al-Air energy storage depends on resolving existing challenges, including electrolyte degradation, as well as preventive self-discharge steps and mechanical recharge methods (Lee *et al.* 2023). Experts investigate combinations of Al-Air batteries, supercapacitors, and redox flow batteries to achieve improved systems with superior cycle performance and efficiency. Research into aluminum anode recycling is receiving attention to establish a more economical and environmentally friendly energy storage system (Lv *et al.* 2023). Research and innovation will surpass ongoing technical challenges in aluminium-air battery infrastructure, thus enabling industrial transformation through an environmentally friendly and cost-effective alternative power solution.

8. CONCLUSION

Aluminium-air batteries show significant potential as an alternative energy storage solution due to their high energy density and environmental benefits. These batteries are particularly suitable for long-duration storage applications, including electric vehicles (EVs) and grid storage systems. However, the practical use of Al-Air batteries is currently limited by several technical challenges.

A major limitation of Al-Air batteries is the mechanical recharge process. Unlike lithium-ion batteries, Al-Air systems are non-rechargeable in the traditional sense. Instead of using an electrical recharge method, the consumed aluminium anode must be physically replaced. This presents logistical challenges, as it requires a robust infrastructure for replacing the anodes. The need for a physical replacement system limits the convenience and practicality of Al-Air batteries, especially in dynamic applications such as electric vehicles, where fast and efficient recharging is crucial (Yang *et al.* 2023). Additionally, Al-Air batteries face other challenges, such as anode corrosion, electrolyte degradation, and limited cycle life (Zou *et al.* 2023). Ongoing research is focusing on overcoming these issues by developing advanced protective coatings for the anode, more stable electrolytes, and hybrid systems that integrate Al-Air batteries with supercapacitors or redox flow batteries (Li *et al.* 2023). These advancements aim to enhance the performance and lifespan of Al-Air batteries. In conclusion, while Al-Air batteries offer considerable advantages, their commercial adoption is hindered by technical limitations, especially related to rechargeability. Addressing these challenges, particularly the mechanical recharge process, is essential for Al-Air batteries to become a viable alternative to conventional rechargeable technologies. Future research and innovation will be key to overcoming these barriers and unlocking the full potential of Al-Air battery technology.

Future Research Directions

- Although significant progress has been made, several challenges remain before Al-Air batteries achieve widespread commercialization. Future research should focus on:
- Developing self-healing anode coatings to reduce self-corrosion further.
- Enhancing rechargeability by optimizing aluminium re-deposition techniques.
- Exploring solid-state electrolytes for improved long-term stability.
- Scaling up hybrid Al-Air energy storage systems for grid applications.
- With continued advancements in material science and electrochemical engineering, Al-Air batteries have the potential to become a disruptive energy storage solution in the coming decades

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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