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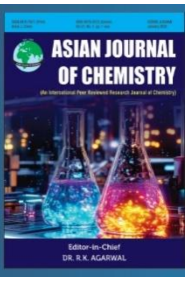

REVIEW

Hydrogen-Oxygen Fuel Cells: Principles, Materials and Applications

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Hydrogen-oxygen (H_2/O_2) fuel cells offer a promising clean energy solution by converting the chemical energy from hydrogen and oxygen into electricity, with water as only the byproduct. This review outlines the principles behind H_2/O_2 fuel cells, including electrochemical reactions, thermodynamic considerations and the role of advanced materials like catalysts, membranes and electrodes. It addresses key challenges such as catalyst degradation, water management and hydrogen storage, alongside strategies to overcome these issues, including non-precious metal catalysts, high-temperature proton-exchange membranes and optimized cell designs. The diverse applications of H_2/O_2 fuel cells, spanning transportation, stationary power generation and portable devices, highlight their potential to decarbonize various industries. The importance of green hydrogen production from renewable energy sources was emphasized and the need for infrastructure to support large-scale fuel cell deployment. As fuel cell technology advances, the transition to a hydrogen economy provides a pathway to achieving net-zero carbon emissions. Continued interdisciplinary research and development are crucial to overcoming existing barriers, enhancing scalability and ensuring the widespread adoption of H_2/O_2 fuel cells as a key component of sustainable energy systems.

Keywords: Fuel cells, Energy conversion, Photovoltaic, Energy efficiency, Energy consumption, Net-zero carbon emissions.

INTRODUCTION

Fuel cells are electrochemical devices that convert the Gibbs free energy change ($-\Delta G$) of a controlled fuel oxidation reaction directly into electrical energy (nFE_{cell}) with high efficiency and minimal environmental impact, bypassing combustion. The reaction occurs through two half-reactions at the electrodes, with ion transport facilitated by an electrolyte or ion-exchange membrane [1]. Unlike conventional batteries, fuel cells require a continuous supply of reactants to sustain operation, delivering a steady voltage output under normal conditions. This enables them to operate efficiently and meet varying energy demands. The relationship between $-\Delta G$ and E_{cell} is expressed by eqn. 1.

$$-\Delta G = nFE_{cell} \qquad (1)$$

where n, F and E_{cell} are the number of electrons involved in the half-reactions (per mole of reactant), the Faraday constant (96.485 C mol^{-1}) and the electromotive force (EMF) or cell potential, representing the maximum potential difference when no current flows. Unlike combustion systems, fuel cells operate without burning fuel, eliminating harmful emissions. Their ability to provide continuous power with a steady fuel supply makes them ideal for transportation, stationary power generation and portable devices.

To locate research articles published in English related to hydrogen-oxygen fuel cells, the authors performed a literature review from 1997 to 2024. The databases explored included Google Scholar, ACS, Taylor & Francis, Scopus, Wiley Online Library, Science Direct and MDPI. The terms used included hydrogen oxygen fuel cells, methods of hydrogen production, electrochemical performance, hydrogen evolution reaction, single atom catalysis, oxygen reduction, non-precious metal catalysts and high-temperature proton-exchange membranes.

Brief history of H_2/O_2 fuel cells: The development of the hydrogen-oxygen (H_2/O_2) fuel cells dates to the 19th century, with the first fuel cell being demonstrated by Sir William Grove in 1839. Grove's "gas voltaic battery" laid the foundation for modern fuel cell technology, utilizing hydrogen and oxygen

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to produce electricity [1]. Over the years, several types of fuel cells have been developed, including alkaline fuel cells (AFCs), which gained prominence in the 1960s for space applications [2] and phosphoric acid fuel cells (PAFCs), which became commercialized in the 1980s for stationary power generation [3]. Proton-exchange membrane fuel cells (PEMFCs) and anion exchange membrane fuel cells (AEMFCs) have emerged as key technologies, with PEMFCs being widely researched for automotive applications due to their high energy density and efficiency. The evolution of these technologies has significantly contributed to the advancement of fuel cell applications in energy conversion systems.

Working principles of H_2/O_2 fuel cell types: Each fuel cell type operates based on similar principles but with different electrolytes and ion migration media, leading to distinct performance characteristics. AFCs use a liquid alkaline electrolyte (typically KOH), where hydroxide ions (OH^-) migrate from the cathode to the anode.

The anodic half-reaction (eqn. 2):

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \tag{2}$$

The cathodic Half-reaction (eqn. 3):

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \text{ (basic environment)} \tag{3}$$

The overall reaction is given in eqn. 4:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Energy} \tag{4}$$

As illustrated in Fig. 1a, this process efficiently converts chemical energy into electrical energy. AFCs are reliable and effective technology, particularly suited for applications such as aerospace systems. PAFCs use liquid phosphoric acid (H_3PO_4) as electrolyte, where hydrogen ions (H^+) migrate from the anode to the cathode.

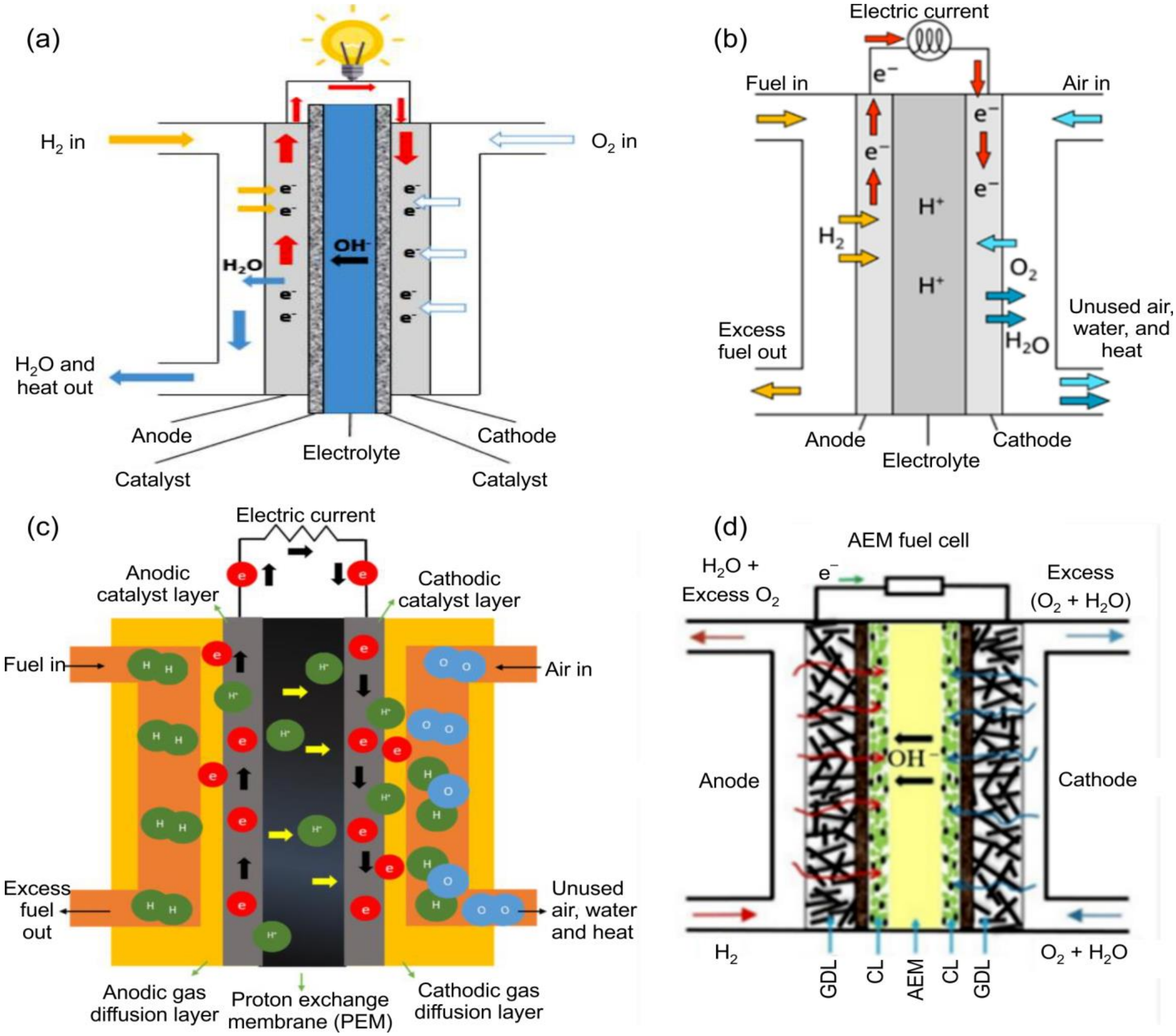

Fig. 1. Schematic illustration of (a) an alkaline fuel cell [7], (b) a phosphoric acid fuel cell [8], (c) proton-exchange membrane fuel cell [9] and (d) anion exchange membrane fuel cell [19]

The anodic half-reaction (eqn. 5):

$$H_2 \rightarrow 2H^+ + 2e^- \text{ (acidic environment)} \tag{5}$$

The cathodic half-reaction (eqn. 6):

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{6}$$

Thus, this results in the same overall reaction depicted in eqn. 4.

Proton exchange membrane fuel cells (PEMFCs) operate with a solid polymer electrolyte, typically Nafion®, which facilitates the migration of hydrogen ions (H^+) between the anode and cathode. Other perfluorosulfonic acid (PFSA) membranes include Aquivion® (Solvay) and Flemion® (Asahi Glass Co.). In addition, the hydrocarbon-based membranes such as sulfonated polyether ether ketone (SPEEK), sulfonated polyimides (SPIs), sulfonated poly(arylene ether sulfone) (SPAES) and polybenzimidazole (PBI) with phosphoric acid doping are also employed. Some composite membranes used include zeolite-embedded membranes, SiO_2 or TiO_2 nanoparticles, ionic liquid-infused polymers and graphene oxide-based membranes. Research activities are in progress to develop advanced proton conducting membranes, such as metal-organic frameworks (MOFs) and proton-conducting ceramics. The half-reactions in PEMFCs are identical to those in phosphoric acid fuel cells (PAFCs). PEMFCs are widely used in transportation applications, including fuel cell-powered vehicles such as cars, buses and forklifts, due to their high efficiency and low emissions. They are also employed in stationary power generation and portable power systems, offering reliable energy solutions for backup power, remote locations and military operations [4].

Anion exchange membrane fuel cells (AEMFCs) utilize a solid anion-exchange membrane (AEM) as the electrolyte, which facilitates the transport of hydroxide ions (OH^-) from the cathode to the anode. This movement of hydroxide ions enables electrochemical reactions essential for power generation. Commercially available AEMs, such as PiperION® and FAA-3 are commonly used in AEMFCs due to their excellent ionic conductivity, mechanical stability and chemical durability under alkaline conditions. The electrochemical half-reactions occurring in AEMFCs are identical to those in phosphoric acid fuel cells (PAFCs), with hydrogen oxidation taking place at the anode and oxygen reduction occurring at the cathode. Overall, the cell combines hydrogen and oxygen to produce water and electricity without emitting harmful pollutants, making AEMFCs a promising technology for sustainable energy applications.

AEMFCs have a range of applications due to their ability to operate efficiently under alkaline conditions and use non-noble metal catalysts. These include portable power devices, residential and backup power, fuel cell vehicles, such as small cars, motorcycles and scooters and in decentralized energy systems to provide power to remote and off-grid locations. Their quiet operation and low detectability make them suitable for military drones, communication devices and portable power supplies in field operations. AEMFCs are utilized in the integrated systems for hydrogen production and consumption, facilitating a clean energy cycle in renewable energy applications and also being researched for use in the hybrid systems combining fuel cells with electrolyzers to store and utilize renewable energy effectively [5,6]. Fig. 1 illustrates the essential components and working principles of the four types of H_2/O_2 fuel cells while Table-1 summarizes their key features.

Thermodynamic and electrochemical performance of hydrogen-oxygen fuel cell: The operation of hydrogen-oxygen fuel cells is governed by key thermodynamic parameters *viz.* enthalpy (ΔH), entropy (ΔS) and Gibbs free energy (ΔG). For the hydrogen-oxygen reaction, the standard enthalpy change (ΔH^o) is –285.83 kJ mol^{-1} and the standard Gibbs free energy change (ΔG^o) is –237.13 kJ mol^{-1} at 298 K. The maximum efficiency (η_{max}) of a fuel cell, representing the fraction of energy converted into electrical work, is given by the ratio of ΔG to ΔH and is approximately 83% under standard conditions. This highlights the high potential for fuel cells in efficient energy conversion.

The polarization curve (Fig. 2) illustrates the relationship between cell potential and current density, showing key loss mechanisms like activation losses (slow reaction kinetics), ohmic losses (resistance to electron and ion flow) and mass transport losses (inadequate reactant supply or water buildup). These losses can be minimized through effective catalysts, high-conductivity materials, optimized hydration and improved gas diffusion layers (GDLs). Regular system optimizations (temperature, pressure, humidity control) and advanced

TABLE-1
IMPORTANT FEATURES OF H_2/O_2 FUEL CELLS

Feature	AFC	PAFC	PEMFC	AEMFC	Ref.
Electrolyte	Liquid KOH	Liquid H_3PO_4	Solid polymer PEM (*e.g.*, Nafion®)	Quaternary ammonium-based polymers	[10]
Operating temperature range	50-200 °C	150-200 °C	50-100 °C	50-100 °C	[11]
Conducting ion	H^+	OH^-	H^+	OH^-	[11]
Catalyst*	Precious and non-precious metals (*e.g.*, Pt, Ni, *etc.*)	Pt	Pt	Non-precious metals like Ni, MnO_2	[12]
Need for GDL and Water Management	Low (electrolyte is liquid)	Moderate (liquid electrolyte)	High (requires precise water management and GDL)	High (requires GDL and hydration management)	[11]
Applications	Aerospace, stationary power	Stationary power generation	Transportation, Portable power	Transportation, Portable and Stationary power	[13]
Challenges	CO_2 sensitivity, electrolyte carbonization	High cost, low power density	Membrane hydration, high cost of Pt	Membrane stability, CO_2 sensitivity	[14]

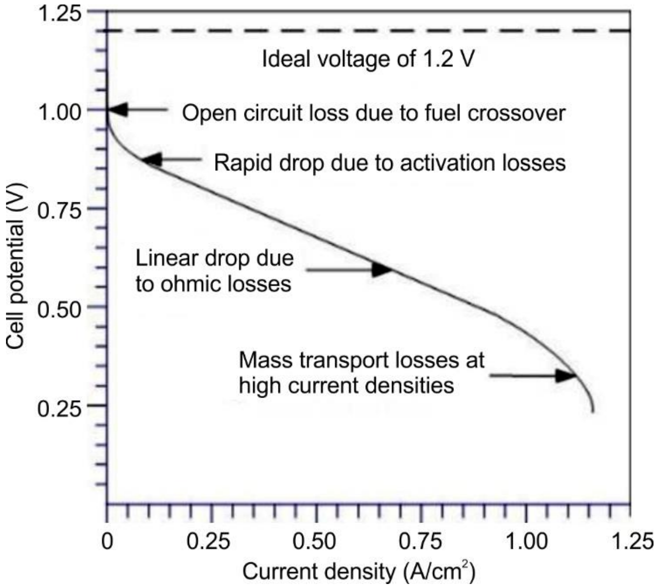

Fig. 2. Typical polarization curve of a PEM fuel cell [15]

materials like perovskites enhance performance. Power density (P) is given by eqn. 7:

$$P = V \times J \quad (7)$$

where V is the operating voltage and J is the current density. High power density is desirable for compact, efficient fuel cell designs. Efficiency is influenced by thermodynamic, electrochemical and fuel utilization factors. The overall efficiency ($\eta_{overall}$) is given by eqn. 8:

$$\eta_{overall} = \eta_{thermodynamic} \times \eta_{fuel} \quad (8)$$

This approach highlights the importance of minimizing losses and maximizing reactant utilization to achieve optimal fuel cell performance.

Methods of hydrogen production: Hydrogen is predominantly produced through several methods, each with distinct environmental impacts and efficiencies. Steam methane reforming (SMR), the most common method, produces gray hydrogen, which involves the extraction of hydrogen from natural gas but releases significant amounts of carbon dioxide (CO_2) into the atmosphere. A more sustainable approach is electrolysis, which splits water into hydrogen and oxygen using electricity. When electricity is sourced from renewable energy such as wind or solar power, this process is termed 'green hydrogen,' as it produces minimal carbon emissions. Another method of hydrogen production is biomass gasification, where organic materials are converted into hydrogen gas. Integrating carbon capture and storage (CCS) technology with SMR can mitigate CO_2 emissions, producing 'blue hydrogen,' which is considered a cleaner alternative to gray hydrogen. Fig. 3 provides a comparison of these current hydrogen production methods and their projected developments by 2050, highlighting advancements in green hydrogen production and the potential for carbon-neutral hydrogen production in future.

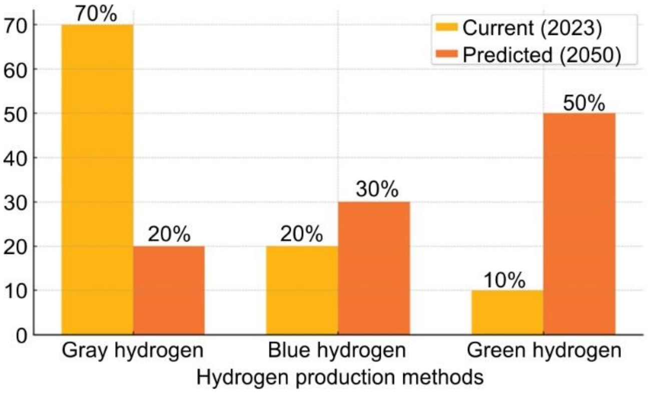

Fig. 3. Hydrogen production methods (2023 *vs.* 2050 projections) [16]

Hydrogen storage, transportation and distribution: Hydrogen storage and transportation face challenges due to its low density and high diffusivity [17]. Key storage techniques include compressed gas [18], commonly used in transportation but requiring high-pressure tanks; liquid hydrogen, which offers higher energy density but is energy-intensive due to liquefaction [19] and solid-state methods involving metal hydrides, chemical carriers and adsorptive materials, providing compact solutions with some limitations. Emerging materials like MOFs, CNTs and COFs, with their high surface area and tunable properties, hold promise but face durability and cost challenges. Table-2 compares these storage methods, highlighting their advantages and limitations. Hydrogen transportation can occur *via* pipelines for long distances or by trucks/rail using compressed or liquid hydrogen. On-site electrolysis eliminates transportation challenges and supports localized supply chains. However, the infrastructure required for large-scale hydrogen transportation, such as pipelines and refueling stations, remains a significant barrier to widespread adoption.

TABLE-2
COMPARISON OF HYDROGEN STORAGE SYSTEMS [17-19]

Storage technique	Advantages	Challenges
Compressed gas storage	Mature technology; widely used; suitable for transportation.	Requires high-pressure tanks; high cost; safety concerns due to leaks.
Liquid hydrogen storage	High energy density; suitable for large-scale and transportation applications.	High energy demand for liquefaction; boil-off losses; cryogenic infrastructure needed.
Metal hydrides	High volumetric density; safe and compact.	Heavy materials; slow hydrogen release rates; cycling stability issues.
Chemical carriers	Stable under ambient conditions; easy transport.	Energy-intensive regeneration; limited scalability.
MOFs and COFs	High surface area; lightweight; tunable porosity for optimized storage.	High synthesis cost; durability under cycling conditions.
Carbon nanotubes (CNTs)	Lightweight; excellent adsorption properties.	Limited storage capacity at ambient temperature; challenges in scalability.

Challenges in hydrogen supply chain: Key challenges in developing a robust hydrogen supply chain include storage, production and refueling infrastructure, with safety, cost reduction and minimizing environmental impacts being significant concerns, especially for green and blue hydrogen. The high flammability of hydrogen necessitates stringent safety measures such as leak detection and proper containment systems. Moreover, the high cost of green hydrogen production combined with the expenses associated with transportation and storage systems such as cryogenic tanks or high pressure vessels, adds the substantial financial burden. The development of the required infrastructure is capital intensive and often geographically challenging, further complicating efforts to establish an efficient and cost-effective hydrogen supply chain. Moreover, regulatory frameworks and public acceptance of hydrogen infrastructure play crucial roles in overcoming these challenges, requiring the coordination between governments, industries and research institutions

Materials for H_2/O_2 fuel cells: The materials used in the hydrogen-oxygen (H_2/O_2) fuel cells are crucial for their efficiency, durability and cost-effectiveness. These include electrode materials, catalysts, proton-exchange membranes, gas diffusion layers and bipolar plates, all essential for electrochemical reactions and overall performance. Table-3 summarizes novel electrode materials and their application as anode/cathode.

Catalysts for hydrogen evolution reaction (HER): Catalysts play a vital role in improving kinetics and energy efficiency of the hydrogen evolution reaction (HER). The platinum-based catalysts remain the standard, but high costs have driven research into alternative, low-cost materials. Non-noble metals such as nickel and cobalt alloys have shown potential, especially in alkaline fuel cells. Table-4 compares novel catalysts for the hydrogen evolution reaction (HER).

Catalysts for oxygen reduction reaction (ORR): The oxygen reduction reaction (ORR) is critical for hydrogen fuel cell efficiency, but it suffers from slow kinetics, requiring effective catalysts. Platinum alloys, such as those with nickel, cobalt or iron, improve ORR by modifying the electronic properties of platinum, reducing platinum content and lowering costs. Core-shell designs, with platinum over a cheaper metal core, further minimize platinum usage while maintaining performance. Iridium oxide (IrO_2) combined with platinum enhances catalyst durability in acidic environments. Non-noble metal catalysts like iron-nitrogen-carbon (Fe-N-C) composites are promising in alkaline media but face challenges in acidic conditions. Single-atom catalysts (SACs) offer high atomic efficiency and tunable properties, although scalability and stability remain issues. Metal-organic frameworks (MOFs) provide customizable, efficient structures, but their high cost and stability under operating conditions pose challenges. Montmorillonite-conducting polymer hybrids offer platinum-like performance but require further research to improve long-term durability. Table-5 summarizes key ORR catalysts, showing that while platinum-based catalysts remain the gold standard, alternative materials like Fe-N-C composites, SACs and MOFs are advancing rapidly, offering promising pathways for cost reduction and performance improvement.

Supported catalysts: Nanostructured carbon materials and zeolite-A are versatile supports for metal oxides and platinum (Pt) catalysts in ORR for acidic and alkaline fuel cells. High-cost oxides such as cerium oxide (CeO_2) and tungsten trioxide (WO_3) offer excellent performance, but low-cost alternatives like titanium dioxide (TiO_2) and manganese dioxide (MnO_2) are gaining attention due to their affordability and catalytic properties. TiO_2 is known for its strong metal-support interaction and stability, particularly when combined with platinum

TABLE-3
NOVEL ELECTRODE MATERIAL APPLICATIONS AND KEY CHARACTERISTICS

Electrode material	Application	Key characteristics	Ref.
Nanostructured carbon or zeolite-A	Cathode (PEMFC, PAFC)	Supports metal oxides and platinum, reduces Pt loading costs.	[19-25]
Nickel foam	Anode (AFC)	Cost-effective hydrogen oxidation catalyst, moderate activity.	[26,27]
Titanium oxide supported catalysts	Anode/cathode (PEMFC)	High stability, corrosion-resistance, supports platinum.	[28]
Graphene/carbon black hybrid	Cathode (PEMFC)	High electrical conductivity, durability, corrosion resistance.	[29-31]

TABLE-4
COMPARISON OF NOVEL CATALYSTS FOR THE HYDROGEN EVOLUTION REACTION (HER)

Catalyst type	Advantages	Drawbacks	Ref.
Pt-based core-shell structures	Exceptional HER activity; high durability	High cost; limited platinum availability.	[32-34]
Nickel based	Cost-effective; good activity in alkaline media.	Lower efficiency in acidic media; prone to poisoning.	[35]
Cobalt based	Affordable; decent HER activity in both acidic and alkaline media.	Moderate efficiency; degradation under prolonged cycling.	[36-39]
Molybdenum based	Abundant; excellent performance in acidic and alkaline media.	Lower activity compared to platinum. Requires further optimization.	[39-43]
Phosphides	High stability; good performance in both media	Sensitive to synthesis conditions; moderate durability.	[44-46]
Other chalcogenides	High catalytic activity for HER; tunable properties (*e.g.*, sulfides, selenides).	Prone to cycling degradation; synthesis complexity.	[47,48]
Metal-organic frameworks (MOFs)	High surface area; tunable catalytic sites for HER.	High synthesis cost; limited long-term stability.	[49-52]

TABLE-5
COMPARISON OF CATALYST FOR OXYGEN REDUCTION REACTION (ORR)

Catalyst type	Advantages	Drawbacks	Ref.
Platinum-based	Excellent ORR activity; stability in acidic environments.	High cost; limited availability; degradation.	[53-58]
Pt Alloys (Pt-Ni, Pt-Co, Pt-Fe)	Enhanced activity; reduced Pt content; cost-effective.	Alloy instability; synthesis complexity.	[59-63]
Core-shell catalysts	Minimized Pt usage; high performance.	Synthesis challenges; durability concerns.	[64-66]
Pt-IrO_2 composites	High stability in acidic environments; enhanced ORR activity.	High cost of Ir; scalability issues.	[67]
Fe-N-C composites	Cost-effective; good activity in acidic and alkaline systems.	Lower activity in acidic media; durability issues.	[68]
Single-atom catalysts (SACs)	High atomic efficiency; tunable activity	Complex synthesis; scalability issues.	[69,70]
Metal-organic frameworks (MOFs)	Tunable properties; high surface area; versatile design.	Stability under operating conditions; high cost.	[71-73]
Montmorillonite-conducting polymer hybrids	Comparable to Pt at same loading; cost-effective.	Limited durability in harsh conditions; optimization required.	[74-76]

catalysts, enhancing ORR activity and durability. MnO_2, with its redox properties, is cost-effective for ORR in alkaline media. Zeolite-A supports further improved catalyst performance by providing a high surface area and enhancing platinum dispersion. Table-6 presents key features of supported catalysis for ORR.

Single metal atom catalysis for HER and ORR: Single-atom catalysis (SAC) enhances electrochemical reactions like hydrogen evolution (HER) and oxygen reduction (ORR) by isolating metal atoms on high-surface-area supports, maximizing atomic utilization and reducing reliance on precious metals. In HER, SACs follow the Volmer-Heyrovsky-Tafel process, where metal atoms adsorb protons to form hydrogen intermediates that desorb as H_2. In ORR, metal atoms activate oxygen molecules, facilitating electron transfer in either a two-electron or four-electron pathway. SAC efficiency depends on the electronic properties of metal, which can be tuned by modifying the support material, such as carbon nanotubes (CNTs), graphene or TiO_2. Common deposition methods include atomic layer deposition (ALD), chemical vapour deposition (CVD) and wet-chemical techniques. Despite challenges in atom stability and uniform dispersion, SACs, using metals like Pt, Pd, Ni, Fe, Co and Cu, offer a sustainable alternative to traditional nanoparticle catalysts.

Key components and computational advances in H_2/O_2 fuel cells: Proton-exchange membranes (PEMs) are critical components of H_2/O_2 fuel cells, with Nafion being the benchmark due to its excellent proton conductivity, mechanical stability and chemical resistance. However, its performance declines at high temperatures and low humidity, prompting the development of alternatives like high-temperature PEMs based on polybenzimidazole (PBI) doped with phosphoric acid, which can operate up to 200 ºC. Composite membranes with inorganic nanoparticles such as silica or titanium dioxide further enhance water retention and thermal stability. Gas diffusion layers (GDLs), typically made of carbon paper or cloth, facilitate reactant transport and water removal, with nanostructured materials like graphene improving conductivity and permeability. Bipolar plates, separating individual cells in a fuel cell stack, are now made from composite materials that combine graphite's conductivity with the durability of metals. Computational tools, including density functional theory (DFT), molecular dynamics (MD) simulations and machine learning (ML), play an increasingly vital role in material design for fuel cells, enabling rapid screening of catalysts, membranes and electrode materials, as well as modeling fuel cell behaviour to improve performance and durability.

Sustainable development and emerging trends in H_2/O_2 fuel cells: The sustainable development of hydrogen-oxygen (H_2/O_2) fuel cells hinges on optimizing performance and addressing recycling challenges. Key performance factors such as power density, durability, fuel utilization efficiency and cost are critical for their practical viability. Advances in catalyst design, high-conductivity materials and cell architecture have improved power density, while alloying and protective coatings help mitigate catalyst degradation. Innovations in membrane technology and system integration are also vital for improving fuel utilization and reducing operational costs. Alongside performance, recycling and end-of-life management are crucial for sustainability. The scarcity and cost of platinum group metals (PGMs) in catalysts pose significant recycling challenges. Techniques like hydrometallurgy, pyrometallurgy and bioleaching aid in recovering PGMs, while studies on recyclable proton-exchange membranes (PEMs) reduces environmental impact. Adopting circular economy principles such as designing for recyclability and extending component life, which supports waste reduction and resource

TABLE-6
SUPPORTED CATALYSTS FOR OXYGEN REDUCTION HALF-REACTION

Catalyst supports	Key advantages	Notable metal oxides	Applications	Ref.
Nanostructured carbon	High surface area, good Pt dispersion	TiO_2, MnO_2	Acidic & alkaline ORR	[77-82]
Zeolite-A	High surface area, ion-exchange capacity	TiO_2, MnO_2	Acidic & alkaline ORR	[83]
TiO_2	Strong metal-support interaction, stability	TiO_2	Pd-catlyzed ORR	[84,85]
MnO_2	High redox activity, cost-effective	MnO_2	Alkaline ORR	[86-90]

conservation. Policymakers are increasingly encouraging these sustainable practices, promoting a circular approach to fuel cell technology.

Looking ahead, the future of H_2/O_2 fuel cells is bright, with applications expanding in sectors like transportation, energy storage and urban infrastructure. Non-precious metal catalysts including iron-nitrogen-carbon composites and single atom catalysts, are reducing costs and enhancing catalytic performance. High-temperature proton-exchange membranes and solid oxide fuel cells are gaining popularity due to their fuel flexibility and ability to operate in demanding conditions. Integrating fuel cells with renewable energy sources such as solar and wind, advances green hydrogen production and contributes to grid stability, aligning with global sustainability goals for net-zero emissions. Through continued innovation, H_2/O_2 fuel cells will be key in the transition to a sustainable, low-carbon energy future.

Conclusion

Hydrogen-oxygen (H_2/O_2) fuel cells represent a transformative technology with the potential to revolutionize energy systems and significantly contribute to environmental sustainability. This study examined their historical development, fundamental working principles and thermodynamic and electrochemical performance, providing a comprehensive understanding of the mechanisms driving their operation. Key components, including advanced electrode and catalyst materials, were critically analyzed, with a focus on emerging innovations such as single-atom catalysis, supported catalysts and computational modeling techniques that enhance performance and durability. Moreover, challenges in hydrogen production, storage and distribution are also highlighted the need for the green hydrogen and efficient supply chain solutions to achieve the widespread adoption. The manuscript also explored operational challenges such as catalyst degradation, water management and system integration, which must be addressed to improve efficiency and scalability. The versatile applications of the fuel cells across transportation, stationary power generation and portable energy systems underline their critical role in global decarbonization efforts. Emerging advancements, including non-precious metal catalysts, high temperature proton-exchange membranes and the integration of solid oxide fuel cells, demonstrate the ongoing progress in this field. As the hydrogen economy evolves, driven by innovations in production technologies and infrastructure development, H_2/O_2 fuel cells are positioned to play a pivotal role in achieving net-zero carbon emissions. Continued interdisciplinary research, focused on overcoming current barriers, driving innovation and optimizing system designs, will enable the broader adoption of this transformative energy technology.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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