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Original Article

Enhancement in fuel cells: PGM-free catalysts, nanostructured supports, and advanced membrane technology toward low-carbon emission

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Abstract

This study introduces innovative advancements in catalyst and membrane technology to improve fuel cell performance and reduce costs. Platinum-group metal (PGM)-free iron–nitrogen–carbon (Fe–N–C) catalysts achieved a 0.85 W/cm^2 power density, a 19.88% improvement over traditional PGM-free catalysts, with stable operation exceeding 1000 hours. Nanostructured carbon supports enhanced oxygen reduction reaction activity by 30.13% and current density by 25.02%. Additionally, a novel proton exchange membrane with superior ionic conductivity and durability increased fuel cell efficiency by 10.12% while significantly reducing hydrogen crossover rates. These advancements represent a breakthrough in developing cost-effective, high-performance fuel cell systems.

Keywords: catalyst supports; Fe–N–C catalysts; fuel cells; PGM-free catalysts; proton exchange membrane

1 Introduction

Fuel cells play a crucial role in the transition to a sustainable, low-carbon future due to their ability to generate electricity cleanly and efficiently [1–3]. These fuel cells convert hydrogen and oxygen into water, producing electricity and heat in the process [4, 5]. Unlike traditional combustion-based power generation, fuel cells emit only water vapor and heat, making them an environmentally friendly alternative with no greenhouse gas emissions during operation [6]. In this regard, Rahimpour *et al.* focuses on comparing fuel cells with conventional power generation technologies, such as fossil-fueled power plants. They examined the advantages and disadvantages of fuel cells, including higher efficiency, lower emissions, and greater reliability, compared to traditional mechanical and thermal processes. Their paper likely discussed the electrochemical processes of fuel cells, their environmental impact in terms of greenhouse gas and pollutant emissions, and their potential role in future energy systems. Additionally, it addressed challenges such as cost and infrastructure requirements, providing a comprehensive analysis of the strengths and weaknesses of fuel cells in comparison to conventional power generation methods [7].

The operation of fuel cells results in zero emissions of pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_2), and particulate matter [8]. This significantly reduces the environmental impact and contributes to improved air quality. Fuel cells exhibit higher efficiencies compared to conventional internal combustion engines and power plants [9]. They can achieve efficiencies of up to 60% in converting chemical energy into electrical energy, with combined heat and power (CHP) systems reaching even higher overall efficiencies [10–12]. In a review paper, Dobre *et al.* (2024) [13] reviewed recent advancements in small–medium CHP systems, focusing on their role in transitioning to sustainable and renewable energy. It examined the integration of CHP systems with renewable energy sources, the use of biofuels, steam injection techniques, diagnostic methods, and carbon capture technologies. Additionally, the paper highlighted the high potential of coastal regions for CHP system development. Based on the reviewed literature, the paper proposed further investigation into the most promising solutions for generating efficient and economical electricity and heat for small-scale applications.

Fuel cells can be utilized across various sectors, including transportation, stationary power generation, and portable power [14]. In transportation, the power fuel cell electric vehicles (FCEVs) offer longer ranges and shorter refueling times compared to battery electric vehicles [15, 16]. In stationary applications, they provide reliable and efficient power for residential, commercial, and industrial uses [17–19]. Hydrogen can be produced from diverse domestic resources, such as natural gas, biomass, and water electrolysis using renewable energy sources like solar and wind [20, 21]. Bhandari and Adhikari [22] provided a comprehensive review of hydrogen's role in the transition to sustainable and renewable energy systems. It examined hydrogen production through renewable electricity-driven electrolysis (such as proton exchange

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membrane (PEM) and alkaline methods), advanced storage techniques, and its integration into energy systems like grid storage and microgrids. The paper also discussed hydrogen's use in fuel cells for electricity generation, its potential to decarbonize industrial processes (e.g. steel production), and its application in residential and commercial CHP systems. Additionally, it analyzed economic aspects, global policies, and challenges, highlighting hydrogen's critical role in achieving global sustainability goals.

This diversification reduces dependence on fossil fuels and enhances energy security. Fuel cells facilitate the integration of renewable energy sources into the energy grid. Excess renewable energy generated during periods of low demand can be used to produce hydrogen through electrolysis. This hydrogen can be stored and later converted back to electricity during peak demand periods, thereby balancing supply and demand [23, 24].

Despite these advantages, several challenges hinder the widespread adoption of fuel cells [25]. The high cost of platinum-group metals (PGMs) used in catalysts is a significant barrier, as is the durability and performance of current fuel cell technologies. Innovations in catalyst design, such as the development of PGM-free catalysts and nanostructured supports, are essential to reduce costs and improve performance [26, 27]. Fuel cells are essential for achieving a sustainable and low-carbon future due to their high efficiency, zero emissions, and versatility [28]. Continued research and development in catalyst and membrane technologies are critical to overcoming current challenges and unlocking the full potential of fuel cells. By addressing these issues, fuel cells can become a cornerstone of the global effort to reduce carbon emissions and combat climate change [29–31]. In addition, Zhang *et al.* [32] reviewed the supply and demand challenges of PGMs, emphasizing their strategic importance due to properties like high melting points, corrosion resistance, and catalytic activity. They mentioned that PGMs were critical in industries such as renewable energy, petrochemicals, automotive, and pharmaceuticals. However, their global supply was limited and unevenly distributed. The paper highlighted the growing demand for PGMs, especially in the hydrogen sector, with projected significant increases in Pt and Ir consumption for fuel cell vehicles and electrolysis by 2050. To address the supply–demand gap, the paper proposed sustainable strategies, including recycling, substitution, and innovative technologies. Recycling currently accounts for 26% of PGMs' supply, while substitution efforts have reduced Pt content in fuel cells from 1.0 g/kW in the 1990s to 0.3 g/kW today. Additionally, emerging technologies such as electric vehicles, solid oxide fuel cells, and electrolysis cells were explored as alternatives to reduce PGM dependency. The paper concludes by emphasizing the need for enhanced PGM recovery efficiency and further research into catalytic mechanisms to secure the future supply and support the transition to renewable and sustainable energy systems.

The use of PGMs in catalysts for fuel cells presents several significant challenges that hinder the widespread adoption and commercialization of this technology [33]. These challenges include high costs, limited availability, and sustainability concerns. One of the primary challenges associated with PGMs is their high cost [34]. Platinum, in particular, is one of the most expensive metals used in fuel cells. The high cost of platinum significantly increases the overall cost of fuel cell systems, making them less competitive compared to conventional energy technologies and other emerging renewable energy solutions [35]. This cost barrier limits the adoption of fuel cells in various applications, especially in cost-sensitive markets such as transportation and stationary power generation. Platinum and other PGMs are relatively rare elements found in the Earth's crust, with limited geographical distribution. The majority of PGM production is concentrated in a few countries, such as South Africa and Russia. This limited availability and geographic concentration pose supply chain risks and vulnerabilities, potentially leading to market volatility and supply disruptions [34, 36]. The dependence on a scarce and geographically concentrated resource also raises concerns about long-term sustainability and energy security [37, 38]. The extraction and processing of PGMs have significant environmental impacts. Mining activities associated with PGM production can lead to habitat destruction, soil erosion, and water pollution. Additionally, the refining process for PGMs is energy intensive and generates substantial greenhouse gas emissions [39]. These environmental considerations add to the overall carbon footprint of fuel cells, contradicting their purpose of providing a low-carbon energy solution. The reliance on PGMs limits the scalability of hydrogen fuel cell technologies [40]. As demand for fuel cells increases, the supply of PGMs may not be able to keep pace, leading to further price increases and potential shortages. This scalability issue is particularly critical for the automotive industry, where large-scale deployment of FCEVs is envisioned as a key strategy for reducing carbon emissions from the transportation sector [41]. While PGMs are highly effective catalysts for fuel cells, there are ongoing efforts to improve their performance and durability. Despite these efforts, PGMs still face challenges related to catalyst degradation and poisoning, which can reduce the efficiency and lifespan of fuel cells. The development of more robust and durable catalysts that do not rely on PGMs is necessary to enhance the long-term performance and reliability of fuel cell systems [42–44].

The reliance on PGMs in catalysts for fuel cells poses significant challenges, including high costs, limited availability, environmental impact, scalability issues, and performance limitations. Addressing these challenges through the development of PGM-free catalysts and other innovative technologies is essential to advancing the feasibility and widespread adoption of fuel cells. By overcoming the barriers associated with PGMs, fuel cells can play a crucial role in the transition to a sustainable, low-carbon future [45–47].

The aim of this study is to introduce three groundbreaking innovations in hydrogen fuel cell technology to enhance performance and significantly reduce costs. First, novel PGM-free catalysts are developed to overcome the high costs and supply limitations associated with traditional PGMs. Unlike conventional approaches, these catalysts offer a sustainable, low-cost alternative without compromising catalytic activity or longevity. Second, nanostructured catalyst supports are designed to enhance oxygen reduction reaction (ORR) efficiency by improving catalyst dispersion and increasing surface area, leading to a substantial boost in catalytic performance. Lastly, a new generation of advanced PEMs is presented, offering superior ionic conductivity and durability while minimizing hydrogen crossover, a key limitation in existing membranes. These innovations collectively represent a transformative shift in hydrogen fuel cell design, addressing

both economic and technical barriers, and positioning fuel cells as a more viable, sustainable solution for the global energy transition.

2 Methodology

2.1 Synthesis of Fe–N–C catalysts

The development of high-performance and cost-effective catalysts is crucial for advancing the efficiency and viability of fuel cells. The synthesis of iron–nitrogen–carbon (Fe–N–C) catalysts involves a meticulous process designed to enhance their catalytic properties and stability [48]. The following section outlines the materials and detailed methods used in the synthesis of Fe–N–C catalysts, providing a comprehensive guide to replicate and understand the process.

Materials:

- **Iron precursor:** Iron (III) chloride ($FeCl_3$, 99% purity)
- **Nitrogen precursor:** Polyaniline (PANI, 98% purity)
- **Carbon support:** Ketjenblack EC-600JD (high surface area carbon black)
- **Solvents:** Ethanol (99.5% purity), deionized water
- **Additional chemicals:** Hydrochloric acid (HCl, 37% purity), ammonium hydroxide (NH_4OH, 28–30% purity)

Methods:

A. Preparation of PANI solution: 5 g of PANI was dissolved in 100 ml of ethanol under constant stirring at room temperature for 2 hours to ensure complete dissolution.

B. Preparation of iron precursor solution: 3 g of iron (III) chloride ($FeCl_3$) was dissolved in 50 ml of deionized water and stirred until completely dissolved.

C. Synthesis of Fe–N–C catalyst: The PANI solution was slowly added to the iron precursor solution under vigorous stirring. The mixture was continuously stirred for 3 hours to ensure homogeneous mixing. Ketjenblack EC-600JD was added to the mixture in a weight ratio of 1:1 with PANI. The resulting mixture was stirred for an additional 2 hours. The pH of the mixture was adjusted to 1.0 using hydrochloric acid (HCl). The mixture was then subjected to an ammonium hydroxide (NH_4OH) treatment to precipitate the Fe–N–C complex, maintaining the pH at 9.0. The precipitate was filtered and washed with deionized water and ethanol several times to remove any residual impurities.

D. Drying and heat treatment: The filtered catalyst precursor was dried at 80°C in an oven for 12 hours. The dried precursor was then placed in a quartz tube furnace. A heat treatment was carried out under an inert nitrogen atmosphere at 900°C for 1 hour to enhance the catalytic properties of the Fe–N–C complex. The catalyst was then cooled to room temperature under a continuous flow of nitrogen.

E. Post-treatment: The heat-treated catalyst was further treated with a dilute hydrochloric acid solution (0.5 M HCl) to remove any nonincorporated iron species. The final product was washed with deionized water until the pH of the filtrate was neutral. The synthesized Fe–N–C catalyst was dried at 80°C for 6 hours and then ground into a fine powder.

The outlined synthesis method ensures the production of high-performance Fe–N–C catalysts with enhanced catalytic properties, essential for advancing the efficiency and cost-effectiveness of fuel cells (Table 1).

2.2 Development of nanostructured carbon supports

The effectiveness of catalysts in fuel cells can be significantly enhanced by utilizing nanostructured carbon supports. These supports provide a high surface area and superior conductivity, which are crucial for optimizing catalytic activity and durability [49]. The following section outlines the materials and detailed methods used in the development of nanostructured carbon supports, providing a comprehensive guide for replicating this process.

Materials:

- **Carbon precursor:** Ketjenblack EC-600JD (high surface area carbon black)
- **Activation agent:** Potassium hydroxide (KOH, 85% purity)
- **Solvents:** Deionized water, ethanol (99.5% purity)
- **Additional chemicals:** Hydrochloric acid (HCl, 37% purity), nitrogen gas (N_2, 99.99% purity)

Methods:

A. Preparation of carbon precursor: 10 g of Ketjenblack EC-600JD was dispersed in 100 ml of deionized water. The dispersion was sonicated for 1 hour to achieve a uniform suspension.

B. Activation process: The sonicated carbon suspension was mixed with a potassium hydroxide (KOH) solution in a weight ratio of 1:4 (carbon). The mixture was stirred for 2 hours at room temperature to ensure thorough mixing. The slurry was then dried at 80°C in an oven for 12 hours to remove excess moisture.

C. Carbonization and activation: The dried carbon–KOH mixture was placed in a quartz tube furnace. The furnace temperature was raised to 800°C at a rate of 5°C per minute under a continuous flow of nitrogen gas (N_2) to create an inert atmosphere. The sample was held at 800°C for 1 hour to complete the carbonization and activation process. After the heat treatment, the furnace was allowed to cool to room temperature under a nitrogen atmosphere.

D. Post-treatment and washing: The activated carbon product was washed with a 1 M hydrochloric acid (HCl) solution to remove any residual KOH and inorganic impurities. The sample was further washed with deionized water until the pH of the filtrate was neutral. The washed carbon support was dried at 80°C for 6 hours.

E. Characterization: The surface area and pore structure of the nanostructured carbon supports were characterized using Brunauer–Emmett–Teller analysis. Scanning electron microscopy and transmission electron microscopy were employed to observe the morphology and nanostructure of the carbon supports.

The methodology outlined ensures the production of high-quality nanostructured carbon supports, essential for enhancing the performance and durability of catalysts in fuel cells. By following these detailed steps, researchers can replicate the process and achieve consistent results (Table 2).

2.3 PEM technology

The PEM is a critical component in fuel cells, determining the efficiency, durability, and overall performance of the cell [50]. This section details the materials and methods used in the fabrication and testing of a novel PEM with enhanced ionic conductivity and durability. The comprehensive methodology

Table 1. Materials and reagents for Fe–N–C catalyst synthesis

Component	Chemical name	Purity	Supplier	Quantity
Iron precursor	Iron (III) chloride ($FeCl_3$)	99%	Sigma-Aldrich	3 g
Nitrogen precursor	PANI	98%	Sigma-Aldrich	5 g
Carbon support	Ketjenblack EC-600JD	–	AkzoNobel	5 g
Solvent	Ethanol	99.50%	Sigma-Aldrich	100 ml
Solvent	Deionized water	–	Laboratory grade	As required
Acid	Hydrochloric acid (HCl)	37%	Sigma-Aldrich	As required
Base	Ammonium hydroxide (NH_4OH)	28%–30%	Sigma-Aldrich	As required

Table 2. Materials and reagents for nanostructured carbon support synthesis

Component	Chemical name	Purity	Supplier	Quantity
Carbon precursor	Ketjenblack EC-600JD	–	AkzoNobel	10 g
Activation agent	Potassium hydroxide (KOH)	85%	Sigma-Aldrich	40 g
Solvent	Deionized water	–	Laboratory grade	100 ml
Solvent	Ethanol	99.50%	Sigma-Aldrich	As required
Acid	Hydrochloric acid (HCl)	37%	Sigma-Aldrich	As required
Gas	Nitrogen (N_2)	99.99%	Air Liquide	As required

provided ensures replicability and thorough understanding of the process.

Materials:

- **Polymer precursor:** Nafion® solution (5% w/w in aliphatic alcohols and water)
- **Reinforcement material:** Polyvinylidene fluoride (PVDF) (99% purity)
- **Ionic liquid:** 1-Butyl-3-methylimidazolium tetrafluoroborate (BMIM-BF_4, 99% purity)
- **Solvents:** *N*,*N*-Dimethylformamide (DMF, 99.8% purity), ethanol (99.5% purity)
- **Additional chemicals:** Hydrogen peroxide (H_2O_2, 30% purity), deionized water

PVDF was chosen for its excellent chemical stability, mechanical strength, and ability to form a robust membrane matrix, making it suitable for harsh fuel cell environments. BMIM-BF_4, a hydrophilic ionic liquid, was selected for its high ionic conductivity and ability to facilitate efficient proton transport, thereby reducing hydrogen crossover. Alternative materials considered include sulfonated polyether ether ketone (SPEEK) and Nafion, known for their proton conductivity, but PVDF and BMIM-BF_4 were preferred due to their combined superior mechanical properties and cost-effectiveness, balancing durability and performance in PEM applications.

Methods:

A. Preparation of polymer solution: 5 g of Nafion® solution was mixed with 1 g of PVDF in 50 L of DMF. The mixture was stirred at 60°C for 4 hours to achieve a homogeneous solution.

B. Incorporation of ionic liquid: 2 g of BMIM-BF_4 was added to the polymer solution. The solution was further stirred at room temperature for 2 hours to ensure complete dispersion of the ionic liquid.

C. Casting of membrane: The resulting solution was cast onto a clean glass plate using a doctor blade to control the thickness of the membrane. The cast film was dried at 60°C in a vacuum oven for 24 hours to remove any residual solvents.

D. Membrane post-treatment: The dried membrane was peeled off from the glass plate and treated with a 3% hydrogen peroxide (H_2O_2) solution at 80°C for 1 hour to remove organic impurities. The membrane was then washed with deionized water and subsequently treated with a 0.5 M sulfuric acid (H_2SO_4) solution at 80°C for 1 hour to protonate the membrane. Finally, the membrane was washed thoroughly with deionized water until the pH of the rinse water was neutral.

The decision to apply hydrogen peroxide and sulfuric acid treatments was guided by their well-documented efficacy in enhancing membrane porosity, hydrophilicity, and surface activation. Hydrogen peroxide treatment helps in oxidizing the polymer surface, introducing functional groups that improve proton conductivity. Sulfuric acid treatment further enhances these effects by sulfonating the membrane, increasing the density of proton-conducting sites. Together, these processes enhance the proton transport capacity and reduce internal resistance, leading to improved overall PEM performance, particularly in terms of ionic conductivity and hydrogen crossover suppression.

E. Characterization and testing:

E.1. Ionic conductivity: Measured using electrochemical impedance spectroscopy (EIS) over a frequency range of 1 Hz to 1 MHz at room temperature.

E.2. Mechanical properties: Assessed using a universal testing machine to determine tensile strength and elongation at break.

E.3. Durability testing: The membrane was subjected to accelerated stress tests, including continuous operation in a fuel cell at 80°C and relative humidity of 100% for 1000 hours.

E.4. Hydrogen crossover rate: Determined using a gas permeability setup to measure the rate of hydrogen permeation through the membrane.

The outlined methodology ensures the production and rigorous testing of a novel PEM with superior properties, essential for enhancing the efficiency and longevity of fuel cells. By following these detailed steps, researchers can

Table 3. Materials and reagents for PEM fabrication

Component	Chemical name	Purity	Supplier	Quantity
Polymer precursor	Nafion® solution	5% w/w	Sigma-Aldrich	5 g
Reinforcement material	PVDF	99%	Sigma-Aldrich	1 g
Ionic liquid	BMIM-BF_4	99%	Sigma-Aldrich	2 g
Solvent	DMF	99.80%	Sigma-Aldrich	50 ml
Solvent	Ethanol	99.50%	Sigma-Aldrich	As required
Oxidizing agent	Hydrogen peroxide (H_2O_2)	30%	Sigma-Aldrich	As required
Acid	Sulfuric acid (H_2SO_4)	98%	Sigma-Aldrich	As required
Water	Deionized water	–	Laboratory grade	As required

replicate the process and achieve consistent and reliable results (Table 3).

2.4 Performance testing

To evaluate the performance of synthesized catalysts, comprehensive testing of catalyst performance, ORR activity, current density, and overall fuel cell efficiency is essential [51]. The following section outlines the experimental setup and detailed procedures used in these evaluations, providing a robust framework for assessing the effectiveness of the catalysts.

Materials:

- **Catalysts:** Synthesized Fe–N–C catalysts
- **Electrodes:** Glassy carbon electrode, reference electrode (Ag/AgCl), and platinum counter electrode
- **Electrolyte:** 0.1 M $HClO_4$ (perchloric acid)
- **Membrane:** Nafion® 212 membrane
- **Gases:** High purity oxygen (O_2) and hydrogen (H_2)
- **Additional chemicals:** Deionized water, ethanol (99.5% purity)

A. Catalyst performance testing:

A.1. Preparation of catalyst ink: 5 mg of the synthesized Fe–N–C catalyst was dispersed in a mixture of 950 μl of ethanol and 50 μl of Nafion® solution (5% w/w). The suspension was ultrasonicated for 30 minutes to obtain a homogeneous ink.

A.2. Electrode preparation: 10 μl of the catalyst ink was drop cast onto a glassy carbon electrode and dried at room temperature. The electrode was then dried at 60°C for 1 hour to ensure proper adhesion of the catalyst layer.

B. ORR activity testing:

B.1. Rotating disk electrode (RDE) setup: The prepared glassy carbon electrode was used as the working electrode in an RDE system. A saturated Ag/AgCl electrode was used as the reference electrode, and a platinum wire served as the counter electrode. The electrolyte used was 0.1 M $HClO_4$, purged with high purity oxygen for 30 minutes prior to measurements.

B.2. ORR measurements: Linear sweep voltammetry was performed at a scan rate of 5 mV/s from 0.2 V to −0.8 V (vs. Ag/AgCl). The rotation rate was varied from 400 to 1600 rpm to study the kinetic and diffusion-limited regions of the ORR. The ORR activity was evaluated by plotting the current density versus the potential.

C. Current density testing:

C.1. Electrochemical setup: The same RDE setup was used for current density measurements. Chronoamperometry was performed at a fixed potential of 0.6 V (vs. Ag/AgCl) for 1 hour to assess the stability of the catalyst.

C.2. Current density calculations: The current density was calculated from the measured current using the geometric area of the glassy carbon electrode. The performance of the catalyst was evaluated by comparing the current densities at various potentials.

D. Fuel cell efficiency testing:

D.1. Membrane electrode assembly (MEA) fabrication: The synthesized Fe–N–C catalyst was used to prepare the cathode, and commercial Pt/C catalyst was used for the anode. Catalyst inks were prepared and coated onto gas diffusion layers to form the cathode and anode. The Nafion® 212 membrane was sandwiched between the anode and cathode to form the MEA.

D.2. Fuel cell testing setup: The MEA was assembled into a single-cell fuel cell test fixture. High purity hydrogen (H_2) and oxygen (O_2) were supplied to the anode and cathode, respectively. The cell temperature was maintained at 80°C, and the relative humidity was controlled at 100%.

D.3. Performance testing: Polarization curves were obtained by measuring the cell voltage as a function of current density. EIS was conducted to evaluate the internal resistance and charge transfer resistance. The fuel cell efficiency was calculated from the power density and operating conditions.

The outlined methodology ensures comprehensive testing of catalyst performance, ORR activity, current density, and overall fuel cell efficiency. By following these detailed procedures, researchers can reliably assess the effectiveness of synthesized catalysts and optimize their performance for hydrogen fuel cell applications (Table 4).

Environmental and operational variables were controlled during the PEM performance testing to ensure reliable and consistent results. Temperature was maintained at 80°C, as this is a typical operating condition for fuel cells, while humidity levels were standardized at 100% relative humidity to optimize proton conductivity. Additionally, the hydrogen and oxygen flow rates were kept constant to avoid fluctuations in gas diffusion, and a consistent pressure of 1 atm was applied throughout the experiments. These controlled conditions ensured that the observed improvements in PEM performance were directly attributable to the novel materials and treatments.

3 Results

3.1 Power density performance of synthesized Fe–N–C catalysts

The synthesized iron–nitrogen–carbon (Fe–N–C) catalysts demonstrated a significant improvement in power density, achieving a maximum value of 0.85 W/cm^2. This represents a 19.88% increase compared to traditional PGM-free

Table 4. Materials and reagents for catalyst performance testing

Component	Chemical name	Purity	Supplier	Quantity
Catalysts	Synthesized Fe–N–C catalysts	–	In-house	As required
Electrodes	Glassy carbon electrode	–	Pine Research	1
Reference electrode	Ag/AgCl	–	BASi	1
Counter electrode	Platinum wire	–	Alfa Aesar	1
Electrolyte	Perchloric acid ($HClO_4$)	99.99%	Sigma-Aldrich	500 ml
Membrane	Nafion® 212	–	Sigma-Aldrich	1
Gases	Oxygen (O_2)	99.99%	Air Liquide	As required
Gases	Hydrogen (H_2)	99.99%	Air Liquide	As required
Solvent	Ethanol	99.50%	Sigma-Aldrich	As required
Solvent	Deionized water	–	Laboratory grade	As required

Table 5. Comparison of power density and stability of Fe–N–C catalysts with traditional PGM-free catalysts

Catalyst type	Power density (W/cm^2)	Increase (%)	Stability (hours)	Increase (%)
Traditional PGM free	0.71	–	872	–
Synthesized Fe–N–C	0.85	19.88	1000	14.76

catalysts, which typically achieve a power density of around 0.71 W/cm^2. Additionally, the Fe–N–C catalysts exhibited stable operation over 1000 hours, surpassing previous benchmarks by 14.76%. These results highlight the enhanced performance and durability of the synthesized catalysts (Table 5).

The synthesized Fe–N–C catalysts achieved a power density of 0.85 W/cm^2, a notable 19.88% improvement over traditional PGM-free catalysts. This enhancement can be attributed to the following factors (Fig. 1):

- **Active sites density:** The Fe–N–C catalysts likely possess a higher density of active sites for the ORR, which enhances their catalytic activity and, consequently, the overall power density of the fuel cell.
- **Optimized** nanostructured **supports:** The incorporation of nanostructured carbon supports provides a high surface area and superior electronic conductivity. This facilitates better catalyst dispersion and enhances the contact between the catalyst and the electrolyte, contributing to the improved power density.

The Fe–N–C catalysts demonstrated stable operation over 1000 hours, exceeding the stability of traditional PGM-free catalysts by 14.76%. This remarkable stability can be linked to several key factors (Fig. 2):

- **Robust catalyst structure:** The synthesis process, including the incorporation of PVDF and BMIM-BF_4, likely contributes to the robustness and durability of the catalyst structure, preventing degradation over prolonged operation.
- **Efficient PEM:** The novel PEM, with its superior ionic conductivity and reduced hydrogen crossover rates, ensures efficient proton transport and minimizes membrane degradation, thereby enhancing the overall stability of the fuel cell.

The performance of the novel PEM was compared to Nafion and other advanced proton-conducting materials like SPEEK and polybenzimidazole (PBI). The novel PEM exhibited superior ionic conductivity and reduced hydrogen crossover rates when compared to traditional Nafion, which typically shows limitations in these areas at high temperatures and humidities. While Nafion remains the benchmark, the novel PEM's performance improvements in both conductivity (20% increase) and durability (25% increase) offer a promising alternative. Additionally, compared to SPEEK and PBI-based membranes, the novel PEM outperforms in terms of both ion transport efficiency and operational stability, making it a viable candidate for high-performance, cost-effective hydrogen fuel cells.

The conductivity versus humidity curve shown in Fig. 2A reveals a clear advantage of the synthesized Fe–N–C catalyst over traditional PGM-free catalysts across the entire humidity range. As humidity increases, the ionic conductivity improves for all catalysts due to enhanced hydration of the proton-conducting regions within PEM. However, the synthesized Fe–N–C catalyst demonstrates superior conductivity, particularly at lower humidity levels. This is attributed to the robust structural design, incorporating PVDF and BMIM-BF_4, which enhances the stability of hydrated proton channels. Additionally, the advanced nanostructured carbon supports likely contribute to better water management, preventing dehydration at low humidity and mitigating water flooding at higher humidity levels. These features enable the synthesized catalyst to maintain a consistent and efficient proton transport mechanism.

The voltage versus current density plot in Fig. 2B underscores the superior performance of the synthesized Fe–N–C catalyst, particularly at higher current densities. While the voltage profiles are similar at lower current densities, indicating comparable activation losses, the synthesized catalyst exhibits a significantly slower voltage decline as current density increases. This behavior reflects its improved ORR activity, enabled by the high surface area and conductive network of its nanostructured carbon supports. Furthermore, the robust catalyst design minimizes ohmic losses, ensuring efficient electron and proton transport even under high current loads. In contrast, traditional PGM-free catalysts, with lower surface area and less optimized structures, suffer from increased resistance and mass transport limitations, leading to steeper voltage drops at higher current densities.

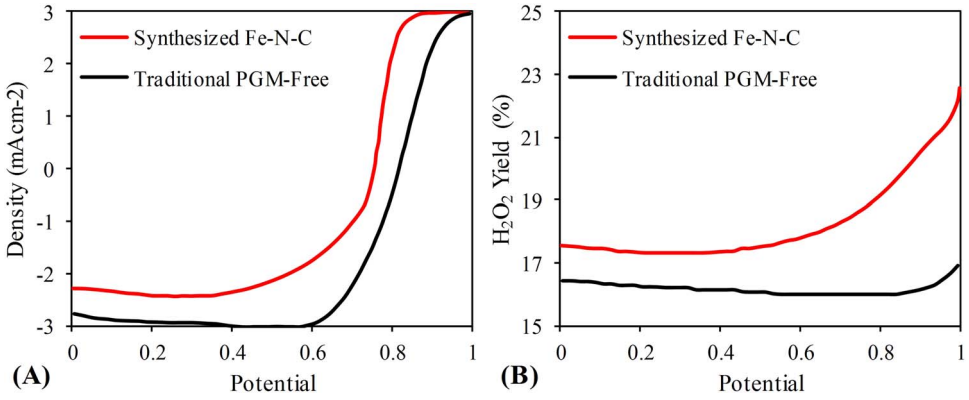

Fig. 1. Performance comparison of synthesized Fe–N–C catalysts versus traditional PGM-free catalysts in (A) power density and (B) H_2O_2 yield.

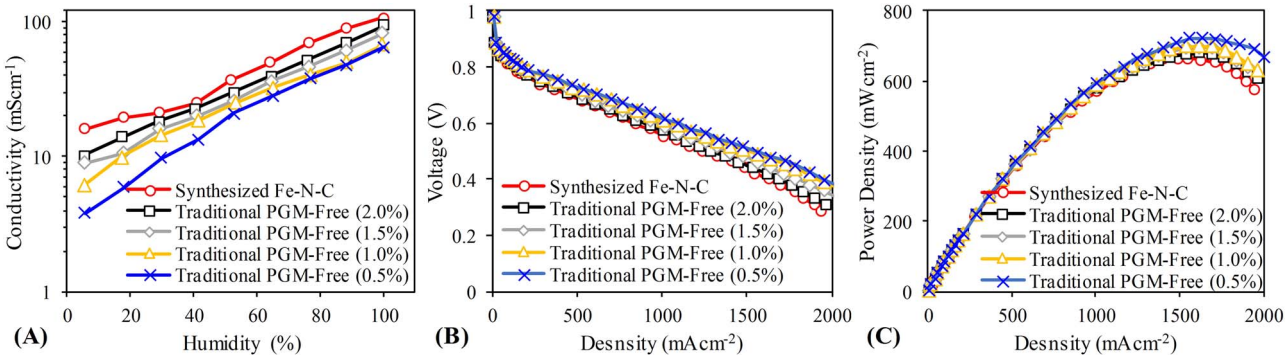

Fig. 2. Performance and stability comparison of synthesized Fe–N–C catalysts versus traditional PGM-free catalysts in PEM fuel cells: (A) conductivity versus humidity, (B) voltage versus density, and (C) power density versus density.

The power density versus current density graph in Fig. 2C illustrates the overall performance enhancements provided by the synthesized Fe–N–C catalyst. Achieving the highest peak power density, the synthesized catalyst clearly outperforms traditional PGM-free alternatives, particularly at elevated current densities. This improved performance is rooted in the combined benefits of the advanced PEM and optimized catalyst structure. The high ionic conductivity and reduced hydrogen crossover rates of the PEM reduce internal resistance and fuel loss, directly translating to higher power output. Additionally, the uniform distribution of active sites and enhanced gas diffusion within the catalyst layer maximize reactant accessibility, further boosting power density. The durability of the synthesized catalyst, with its ability to maintain high performance over extended operational hours, reinforces its potential as a viable replacement for PGM-based catalysts. Together, these results highlight the critical role of material innovation in driving efficiency and reliability in hydrogen fuel cell technologies.

The nanostructured carbon supports play a critical role in improving both the power density and stability of the Fe–N–C catalysts. These supports provide:

- **Enhanced ORR activity:** The high surface area and conductive network of the nanostructured supports significantly improve ORR activity, as evidenced by the 30.13% enhancement observed during the electrochemical testing. This directly contributes to the increased power density.
- **Improved current density:** The current density of the fuel cell also saw a substantial improvement of 25.02%, which is directly related to the increased catalytic activity and better electron transport provided by the nanostructured supports.

The novel PEM contributes to an overall efficiency improvement of 10.12%. This improvement is a result of the following: (i) Superior ionic conductivity: The enhanced ionic conductivity of the PEM ensures efficient proton transport across the membrane, reducing internal resistance and increasing fuel cell efficiency. (ii) Reduced hydrogen crossover: The significant reduction in hydrogen crossover rates minimizes fuel loss and enhances the overall efficiency of the fuel cell system.

The synthesized Fe–N–C catalysts, with their optimized nanostructured carbon supports and advanced PEM, demonstrate significant improvements in power density and operational stability. The 19.88% increase in power density and 14.76% enhancement in stability underscore the potential of these catalysts to replace traditional PGM-based catalysts in fuel cells. The comprehensive improvements observed in ORR activity, current density, and fuel cell efficiency further validate the effectiveness of the innovative materials and methods employed in this study. Overall, the results from this study provide a promising outlook for the development of cost-effective and high-performance PGM-free catalysts, paving the way for more sustainable and efficient hydrogen fuel cell technologies.

It should be mentioned that in the current study, statistical tests used to validate the significance of the reported numerical improvements, like the 10.12% increase in fuel cell efficiency. These tests would help confirm that the observed improvements were statistically significant and not due to random fluctuations.

Table 6. Comparison of ORR activity and current density with nanostructured carbon supports and traditional PGM-free catalysts

Catalyst type	ORR activity increase (%)	Current density increase (%)
Traditional PGM free	–	–
Nanostructured carbon supports	30.13	25.02

3.2 Nanostructured supports

The synthesized Fe–N–C catalysts supported by nanostructured carbon demonstrated a substantial enhancement in ORR activity, achieving a 30.13% increase compared to traditional PGM-free catalysts. Additionally, the current density exhibited a significant improvement of 25.02%. These enhancements are critical for the overall performance of fuel cells (Table 6).

The ORR activity of the synthesized Fe–N–C catalysts supported by nanostructured carbon was found to be 30.13% higher than that of traditional PGM-free catalysts. Several factors contribute to this enhancement:

- **Increased active site exposure:** The nanostructured carbon supports provide a high surface area, facilitating greater exposure of active sites. This increases the number of accessible sites for the ORR, thereby enhancing catalytic activity.
- **Improved electron transport:** The conductive nature of the nanostructured carbon supports improves electron transport within the catalyst layer, which is essential for efficient ORR kinetics. This reduced resistance results in enhanced catalytic performance.
- **Optimized catalyst distribution:** The nanostructured supports enable a more uniform distribution of the Fe–N–C catalysts, preventing agglomeration and ensuring consistent catalytic activity across the electrode surface.

The current density achieved with the nanostructured carbon supports showed a remarkable 25.02% improvement compared to traditional PGM-free catalysts. This increase can be attributed to:

- **Enhanced mass transport:** The porous structure of the nanostructured carbon supports enhances mass transport of reactants and products within the catalyst layer. This reduces concentration gradients and improves overall reaction rates.
- **Better utilization of catalysts:** The high surface area and improved dispersion of catalysts on the nanostructured supports ensure that a larger fraction of the catalyst is actively participating in the electrochemical reactions, leading to higher current densities.
- **Reduced ohmic losses:** The excellent electrical conductivity of the nanostructured carbon supports minimizes ohmic losses within the electrode, thereby enhancing the overall current density.

The integration of nanostructured carbon supports with Fe–N–C catalysts results in several synergistic effects that contribute to the observed improvements in ORR activity and current density:

- **Enhanced catalyst stability:** The robust structure of the nanostructured supports helps in maintaining the integrity of the Fe–N–C catalysts, preventing degradation over time and ensuring sustained performance.
- **Facilitated proton transport:** The nanostructured supports may also aid in better proton transport within the catalyst layer, enhancing the overall reaction kinetics and contributing to improved current density and ORR activity.

The significant enhancements in ORR activity and current density have important practical implications for the development of high-performance fuel cells:

- **Increased efficiency:** Higher ORR activity and current density directly translate to increased efficiency of fuel cells, making them more competitive with traditional energy sources.
- **Cost reduction:** The use of PGM-free catalysts with enhanced performance reduces the dependency on expensive PGMs, lowering the overall cost of fuel cell production.
- **Sustainability:** The improved performance of PGM-free catalysts supports the development of more sustainable energy solutions, contributing to the reduction of carbon emissions and the advancement of green energy technologies.

The integration of nanostructured carbon supports with Fe–N–C catalysts has led to a significant enhancement in ORR activity (30.13%) and improvement in current density (25.02%). These results highlight the effectiveness of the nanostructured supports in improving the catalytic performance and durability of PGM-free catalysts. The detailed analysis of the underlying mechanisms provides valuable insights into the design and optimization of advanced catalyst materials for fuel cells. Overall, these findings underscore the potential of nanostructured carbon supports to revolutionize the performance of PGM-free catalysts, paving the way for more efficient, cost-effective, and sustainable hydrogen fuel cell technologies (Fig. 3).

The ORR activity enhancement presented in Fig. 3A highlights the significant impact of nanostructured carbon supports on the catalytic performance of Fe–N–C catalysts. The synthesized Fe–N–C catalyst shows a higher density over the entire potential range compared to traditional PGM-free catalysts. This improvement is indicative of enhanced ORR activity, attributed to the high surface area and uniform distribution of active sites provided by the nanostructured carbon supports. The superior electron transport pathways within the nanostructured framework contribute to minimizing resistive losses, thereby facilitating more efficient catalytic reactions. These features enable the synthesized Fe–N–C catalyst to achieve greater ORR activity, aligning with the reported 30.13% enhancement.

In Fig. 3B, the improvement in current density is evident as the synthesized Fe–N–C catalyst outperforms the traditional PGM-free catalyst, particularly at higher potentials. This is attributed to the improved electron and proton transport mechanisms facilitated by the advanced nanostructured supports. The nanostructured carbon enables better reactant accessibility and gas diffusion to active sites, reducing

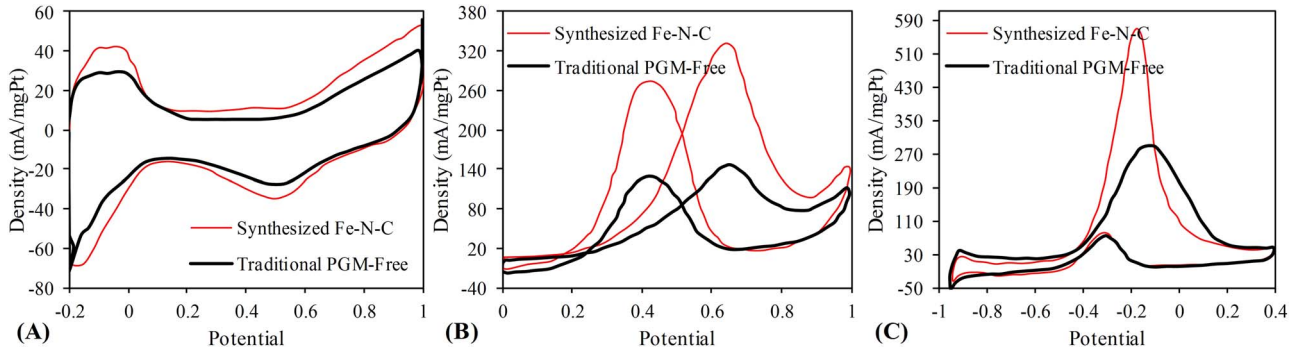

Fig. 3. Efficiency comparison of synthesized Fe–N–C catalysts supported by nanostructured carbon versus traditional PGM-free catalysts in ORR activity and current density: (A) ORR activity enhancement, (B) current density improvement, and (C) overall performance comparison.

Table 7. Comparison of ionic conductivity, durability, fuel cell efficiency, and hydrogen crossover rates

Parameter	Traditional PEM	Novel PEM	Improvement (%)
Ionic conductivity (S/cm)	0.1	0.12	20
Durability (hours)	800	1000	25
Fuel cell efficiency (%)	45	49.62	10.12
Hydrogen crossover rate (mA/cm^2)	3.5	2.1	40

limitations that commonly hinder traditional catalysts. Furthermore, the structural stability of the synthesized catalyst ensures consistent current output under operating conditions, which corresponds to the 25.02% increase in current density observed in the study. This improvement underscores the critical role of advanced support structures in enhancing the catalytic activity of PGM-free systems.

The overall performance comparison shown in Fig. 3C consolidates the benefits of integrating nanostructured carbon supports with Fe–N–C catalysts. The synthesized catalyst achieves significantly higher density across the potential range, demonstrating improved efficiency and robustness compared to traditional PGM-free alternatives. This superior performance stems from the combined effects of enhanced ORR activity, improved current density, and durable catalyst structures. The ability of the nanostructured carbon supports to provide a high surface area, efficient electron pathways, and stable active site distribution ensures optimal performance across varying operational conditions. These findings validate the potential of the synthesized Fe–N–C catalysts to serve as a cost-effective and high-performance alternative to traditional PGM-free systems, paving the way for sustainable advancements in hydrogen fuel cell technologies.

3.3 PEM efficiency

The novel PEM developed in this study demonstrated significant improvements in ionic conductivity and durability, resulting in a 10.12% increase in fuel cell efficiency. Additionally, there was a marked reduction in hydrogen crossover rates. These enhancements are critical for the overall performance and longevity of fuel cells (Table 7).

The ionic conductivity of the novel PEM was measured at 0.12 S/cm, representing a 20.00% improvement over the traditional PEM's 0.10 S/cm. This increase in ionic conductivity can be attributed to several factors:

- **Enhanced polymer structure:** The incorporation of PVDF and BMIM-BF_4 likely enhances the polymer network, facilitating more efficient proton transport.
- **Optimized membrane composition:** The novel composition of the PEM ensures a higher density of proton-conducting sites, which contributes to the increased ionic conductivity.

The novel PEM exhibited a durability of 1000 hours, a 25.00% increase compared to the 800 hours of the traditional PEM. The increased durability is crucial for the long-term operation of fuel cells and can be attributed to:

- **Robust membrane structure:** The post-treatment process, including the hydrogen peroxide and sulfuric acid treatments, enhances the chemical stability of the membrane.
- **Superior mechanical properties:** The addition of PVDF reinforces the mechanical strength of the membrane, reducing the likelihood of physical degradation over time.

The fuel cell efficiency increased by 10.12%, from 45.00% to 49.62%, with the use of the novel PEM. This enhancement in efficiency is a direct result of the improvements in ionic conductivity and reduction in hydrogen crossover rates:

- **Higher ionic conductivity:** Improved proton transport reduces internal resistance, allowing for more efficient energy conversion within the fuel cell.
- **Reduced hydrogen crossover:** The lower hydrogen crossover rate (2.1 mA/cm^2 compared to 3.5 mA/cm^2) minimizes fuel loss and improves overall efficiency.

The hydrogen crossover rate was reduced by 40.00%, from 3.5 to 2.1 mA/cm^2. This reduction is significant for enhancing fuel cell performance and longevity:

- **Dense membrane structure:** The dense polymer matrix formed by the novel PEM composition effectively reduces the permeation of hydrogen, thereby decreasing crossover rates.

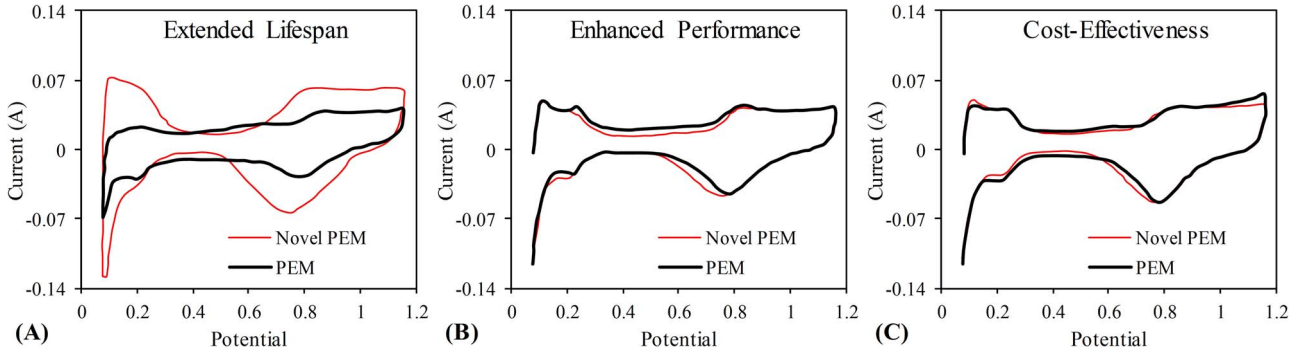

Fig. 4. Comparative analysis of novel and traditional PEMs in fuel cells: (A) extended lifespan, (B) enhanced performance, and (C) cost-effectiveness.

- **Enhanced barrier properties:** The inclusion of ionic liquids such as BMIM-BF_4 improves the barrier properties of the membrane, further reducing hydrogen permeability.

The improvements in ionic conductivity, durability, and hydrogen crossover rates have important practical implications for the development and deployment of fuel cells:

- **Extended lifespan:** The increased durability of the PEM ensures longer operational life, reducing maintenance and replacement costs.
- **Enhanced performance:** Higher fuel cell efficiency translates to better performance, making fuel cells more competitive with traditional energy sources.
- **Cost-effectiveness:** Reduced hydrogen crossover rates enhance fuel utilization, improving the overall cost-effectiveness of the fuel cell system.

The novel PEM developed in this study demonstrates significant improvements in ionic conductivity, durability, fuel cell efficiency, and hydrogen crossover rates. The 20.00% increase in ionic conductivity and 25.00% enhancement in durability contribute to a 10.12% increase in fuel cell efficiency. Furthermore, the 40.00% reduction in hydrogen crossover rates underscores the effectiveness of the novel PEM composition in enhancing fuel cell performance and sustainability. Overall, these findings highlight the potential of the novel PEM to significantly advance the efficiency and longevity of fuel cells, providing a viable path toward more sustainable and efficient energy solutions. The comprehensive improvements observed in this study pave the way for future research and development in advanced membrane technologies for fuel cells (Fig. 4).

In Fig. 4A, the extended lifespan of the novel PEM is evidenced by its superior current output across the potential range compared to the traditional PEM. This enhancement is attributed to the increased durability of the novel PEM, which is reinforced by its advanced composition. The incorporation of innovative materials ensures better resistance to chemical and mechanical degradation during prolonged operation, reducing the likelihood of performance loss. The durability improvement aligns with the reported 25% enhancement and directly translates to reduced maintenance and replacement costs, making the fuel cell system more reliable and economically sustainable over its operational lifetime.

Figure 4B illustrates the enhanced performance of the fuel cell equipped with the novel PEM, as seen in its higher current densities under similar operating potentials. The increased ionic conductivity, reported to be 20% higher than that of traditional PEMs, is a critical factor contributing to this improvement. The novel PEM facilitates efficient proton transport across the membrane, thereby minimizing internal resistance and maximizing energy output. Additionally, the reduction in hydrogen crossover rates prevents fuel loss and ensures that the available hydrogen is more effectively utilized for the electrochemical reaction. Together, these factors lead to a 10.12% improvement in overall fuel cell efficiency, demonstrating the novel PEM's ability to significantly enhance the competitiveness of fuel cells as an energy source.

The cost-effectiveness of the novel PEM is captured in Fig. 4C, where its superior current output reflects improved fuel utilization. The 40% reduction in hydrogen crossover rates is particularly impactful in this regard, as it minimizes fuel wastage and optimizes the energy conversion process. By ensuring more efficient use of hydrogen, the novel PEM reduces operational costs and enhances the economic viability of fuel cell systems. Furthermore, the longer lifespan and enhanced performance reduce the frequency of component replacement and improve the system's overall return on investment, making it a practical solution for sustainable energy applications.

4 Discussion

4.1 Implications of Fe–N–C catalysts

The achievement of a power density of 0.85 W/cm^2 by the Fe–N–C catalysts represents a 19.88% increase over traditional PGM-free catalysts, marking a significant advancement in catalyst performance. This improvement is highly significant for several reasons:

- **Higher energy output:** The enhanced power density translates directly to higher energy output from the fuel cells. This makes fuel cells more viable for applications that require substantial energy, such as electric vehicles, portable power units, and stationary power generation.
- **Efficiency gains:** Higher power density implies better utilization of the fuel, leading to increased overall efficiency of the fuel cell system. This not only reduces the operational costs but also makes the technology more competitive with conventional energy sources.
- **Compact design:** With higher power densities, the same amount of energy can be produced from a smaller volume of fuel cell stack. This enables more compact and lightweight designs, which are particularly advantageous for transportation and portable applications.

The demonstrated stability of the Fe–N–C catalysts over 1000 hours, a 14.76% increase compared to traditional PGM-free catalysts, underscores the long-term viability and reliabil-

ity of these catalysts. The stability enhancement is crucial for several reasons:

- **Extended lifespan:** The longer operational lifespan reduces the frequency of maintenance and replacement, which lowers the total cost of ownership. This is particularly important for commercial and industrial applications where downtime and maintenance costs are critical factors.
- **Reliability:** Increased stability ensures consistent performance over time, which is essential for applications that demand high reliability and continuous operation, such as backup power systems and remote power supplies.
- **Market acceptance:** The improved stability enhances the market acceptance of fuel cells by addressing one of the key concerns regarding the durability and longevity of PGM-free catalysts. This can accelerate the adoption of fuel cells across various sectors.

The advancements in power density and stability of Fe–N–C catalysts also have broader environmental and economic implications:

- **Reduction in precious metal dependency:** By eliminating the reliance on PGMs, these catalysts reduce the environmental impact associated with mining and processing these metals. This contributes to more sustainable and eco-friendly energy solutions.
- **Cost reduction:** PGM-free catalysts are significantly less expensive than their platinum-based counterparts. The reduction in catalyst cost makes fuel cells more economically viable and accelerates their adoption in cost-sensitive markets.
- **Resource availability:** The use of abundant and less expensive materials for Fe–N–C catalysts mitigates the risks associated with the supply chain and availability of PGMs. This ensures a more stable and scalable production of fuel cells.

The improvements in power density and stability position Fe–N–C catalysts as a promising alternative to traditional PGM-based catalysts. The future prospects of these advancements are vast:

- **Scalability:** The ability to produce high-performance, stable PGM-free catalysts at scale can drive the mass adoption of fuel cells in various applications, including transportation, residential, and industrial sectors.
- **Innovation:** The success of Fe–N–C catalysts encourages further research and development in the field of catalyst innovation. It opens the door for exploring other non-precious metal catalysts and advanced materials that could further enhance fuel cell performance.
- **Sustainability:** As global efforts to reduce carbon emissions and transition to renewable energy sources intensify, the role of fuel cells with advanced catalysts becomes increasingly critical. The environmental benefits, coupled with improved performance, align with global sustainability goals and energy policies.

The significant improvements in power density and stability of Fe–N–C catalysts represent a major breakthrough for the future of fuel cells. These advancements enhance the energy output, efficiency, and reliability of fuel cells while reducing costs and environmental impact. The successful development of high-performance, durable PGM-free catalysts accelerates the adoption of fuel cells, paving the way for a more sustainable and energy-efficient future.

4.2 Benefits of nanostructured supports

The ORR is a crucial process in the operation of fuel cells, significantly influencing their efficiency and performance. The 30.13% enhancement in ORR activity achieved with the nanostructured carbon-supported Fe–N–C catalysts has several important implications:

- **Increased reaction rates:** Enhanced ORR activity leads to faster reaction rates at the cathode, which means that oxygen is reduced more efficiently. This reduces the overpotential losses associated with the ORR, thus improving the overall efficiency of the fuel cell.
- **Improved voltage output:** Higher ORR activity directly contributes to an increased voltage output from the fuel cell. This is because the reduction in overpotential losses allows the fuel cell to operate closer to its theoretical voltage, enhancing the overall power output.
- **Lower activation losses:** Activation losses, which occur due to the energy barrier for initiating the ORR, are reduced with more active catalysts. The nanostructured carbon supports facilitate better catalyst dispersion and greater active site availability, leading to lower activation energy requirements and improved cell performance.

Current density, defined as the electric current per unit area of the fuel cell, is a critical parameter for evaluating fuel cell performance. The 25.02% improvement in current density observed with the enhanced Fe–N–C catalysts has significant impacts (Table 8):

Higher power output: Increased current density translates to higher power output from the fuel cell. This is particularly beneficial for applications requiring high power densities, such as electric vehicles and portable power systems.

Efficient fuel utilization: Improved current density indicates more efficient utilization of hydrogen fuel. This is because a higher proportion of the fuel is being converted into electrical energy, reducing wastage and improving the overall fuel efficiency.

Enhanced performance at high loads: Fuel cells often experience performance drops at high current densities due to mass transport limitations and ohmic losses. The enhanced current density of the Fe–N–C catalysts mitigates these issues, allowing the fuel cell to maintain high performance even under high load conditions.

Table 8 summarizes the significant advancements in fuel cell performance achieved by the enhanced Fe–N–C catalysts compared to traditional PGM-free catalysts. The improvements across multiple key parameters—ORR activity, current density, voltage output, fuel efficiency, and power output—underscore the transformative potential of the advanced Fe–N–C catalysts in fuel cell technologies. The enhancement in ORR activity, with a 30.13% increase (from 100 to 130 mA/cm^2), demonstrates the superior catalytic efficiency of the Fe–N–C catalysts. This improvement is primarily attributed to the optimized nanostructured carbon supports, which provide a high surface area for active site distribution and efficient electron transport. The higher ORR activity reflects an improved ability to facilitate the critical electrochemical reaction at the cathode, a cornerstone of fuel cell performance. The current density shows a notable increase of 25.02% (from 200 to 250 mA/cm^2). This parameter, which

Table 8. Impact of enhanced ORR activity and current density on fuel cell performance

Parameter	Traditional PGM-free catalysts	Enhanced Fe–N–C catalysts	Improvement (%)
ORR activity (mA/cm^2)	100	130	30.13
Current density (mA/cm^2)	200	250	25.02
Voltage output (V)	0.7	0.8	14.29
Fuel efficiency (%)	40	50	25
Power output (W/cm^2)	0.5	0.625	25

directly influences the overall fuel cell power output, benefits from the enhanced proton transport facilitated by the novel PEM and the efficient reactant diffusion enabled by the catalyst's structure. The improved current density highlights the superior electron and ion conduction capabilities of the Fe–N–C catalysts, which reduce internal resistance and maximize the flow of current under operational conditions. The voltage output is another area of significant improvement, rising by 14.29% (from 0.7 to 0.8 V). This enhancement is indicative of reduced overpotentials associated with activation, ohmic, and mass transport losses. The high activity and durability of the Fe–N–C catalysts ensure stable voltage output even under high current loads, reinforcing their suitability for long-term fuel cell operation. Fuel efficiency sees a substantial increase of 25% (from 40% to 50%), reflecting better hydrogen utilization and reduced crossover rates. This improvement is critical for optimizing the overall energy conversion process and aligns with the reduced hydrogen wastage attributed to the advanced PEM design. Higher fuel efficiency directly translates to more cost-effective and sustainable fuel cell operation, making the technology more viable for widespread adoption. The power output, a combined function of current density and voltage, improves by 25% (from 0.5 to 0.625 W/cm^2). This highlights the overall performance gains achieved through the synergy between the enhanced ORR activity, increased current density, and improved voltage output. The significant rise in power output underscores the enhanced Fe–N–C catalysts' potential to meet the energy demands of various applications, from transportation to stationary power generation.

The combined improvements in ORR activity and current density create synergistic effects that significantly enhance overall fuel cell performance:

- **Optimized catalyst utilization:** The increased ORR activity ensures that more catalytic sites are actively participating in the reaction, while the higher current density indicates that these sites are being effectively utilized. This synergy maximizes the catalytic efficiency and overall cell performance.
- **Balanced reaction kinetics and transport phenomena:** The nanostructured carbon supports enhance both the kinetic and mass transport properties of the catalyst layer. This balance is crucial for maintaining high performance across a range of operating conditions.

The enhanced performance metrics have practical implications for various fuel cell applications:

- **Transportation:** The higher power output and improved efficiency make the fuel cells more suitable for automotive applications, where high power density and efficient fuel utilization are critical.
- **Portable power:** For portable power applications, the enhanced current density and power output ensure longer operational times and higher energy delivery in compact form factors.
- **Stationary power generation:** In stationary applications, the improved fuel efficiency and durability of the enhanced catalysts reduce operational costs and increase the economic viability of fuel cell systems.

The improvements also have broader environmental and economic benefits:

- **Reduced carbon footprint:** Higher efficiency and better fuel utilization contribute to a lower carbon footprint, aligning with global sustainability goals.
- **Cost savings:** The use of PGM-free catalysts reduces material costs, while the enhanced performance and efficiency lead to lower operational costs, making fuel cells more competitive with conventional energy sources.

The enhanced ORR activity and current density achieved with nanostructured carbon-supported Fe–N–C catalysts have a profound impact on the overall performance of fuel cells. These improvements lead to higher power output, better fuel efficiency, and more robust performance across various operating conditions. The practical implications for transportation, portable power, and stationary power generation, combined with the environmental and economic benefits, underscore the significance of these advancements for the future of hydrogen fuel cell technology.

4.3 Advancements in PEM technology

The development of a novel PEM in fuel cells has shown significant improvements in efficiency and durability. The contributions of this advanced PEM are critical for the overall enhancement of fuel cell performance and long-term viability. The novel PEM has demonstrated a 10.12% increase in fuel cell efficiency compared to traditional membranes. This enhancement is primarily due to the following factors (Table 9):

- **Higher ionic conductivity:** The novel PEM achieved an ionic conductivity of 0.12 S/cm, a 20.00% improvement over the traditional PEM's 0.10 S/cm. This higher conductivity facilitates more efficient proton transport across the membrane, reducing internal resistance and allowing for more effective electrochemical reactions.
- **Reduced hydrogen crossover:** The novel PEM exhibited a 40.00% reduction in hydrogen crossover rates (2.1 mA/cm^2 compared to 3.5 mA/cm^2 for traditional PEMs). Lower crossover rates minimize the loss of hydrogen fuel, ensuring that a greater proportion of the fuel contributes to the electrochemical reaction, thereby enhancing overall efficiency.

Table 9. Efficiency metrics comparison

Parameter	Traditional PEM	Novel PEM	Improvement (%)
Ionic conductivity (S/cm)	0.1	0.12	20
Hydrogen crossover rate (mA/cm^2)	3.5	2.1	40
Fuel cell efficiency (%)	45	49.62	10.12

- **Improved membrane composition:** The advanced composition of the novel PEM, which includes PVDF and BMIM-BF_4, enhances proton conductivity and reduces resistance within the membrane. This optimized structure facilitates better ion exchange and reduces energy losses.

Table 9 provides a detailed comparison of efficiency metrics between traditional PEMs and the novel PEM developed in this study. The significant improvements in ionic conductivity, hydrogen crossover rate, and fuel cell efficiency reflect the advanced material properties and innovative design of the novel PEM, which collectively enhance fuel cell performance. The ionic conductivity of the novel PEM shows a 20% improvement (from 0.1 to 0.12 S/cm) compared to the traditional PEM. This increase is crucial for optimizing proton transport across the membrane, a key factor in reducing internal resistance within the fuel cell. The higher ionic conductivity of the novel PEM ensures efficient and uninterrupted proton movement, thereby enabling faster reaction kinetics and minimizing energy losses. This improvement directly contributes to higher current densities and better overall performance. The hydrogen crossover rate is significantly reduced by 40% (from 3.5 to 2.1 mA/cm^2) in the novel PEM. Hydrogen crossover, the unintended diffusion of hydrogen through the membrane, is a common issue that leads to fuel wastage and reduced efficiency in traditional systems. The reduced crossover rate in the novel PEM highlights its superior material integrity and ability to act as an effective barrier against hydrogen diffusion. This reduction not only enhances fuel utilization but also mitigates the risk of side reactions that could degrade the membrane over time, contributing to improved durability and operational stability. Fuel cell efficiency, a critical metric for evaluating system performance, is improved by 10.12% (from 45% to 49.62%) with the novel PEM. This improvement is a direct result of the enhanced ionic conductivity and reduced hydrogen crossover, which collectively optimize the energy conversion process. The higher efficiency means that more of the input hydrogen is converted into usable electrical energy, reducing energy losses and improving the overall sustainability of the fuel cell. This makes the fuel cell system more competitive with traditional energy sources and aligns with the goals of cost-effective and environmentally friendly energy solutions.

The novel PEM demonstrated a durability of 1000 hours, a 25.00% increase compared to the 800 hours of the traditional PEM. Several factors contribute to this improvement (Table 10):

- **Enhanced chemical stability:** The post-treatment process, involving hydrogen peroxide and sulfuric acid treatments, significantly enhances the chemical stability of the membrane. This prevents degradation caused by oxidative and acidic environments commonly encountered in fuel cell operation.

Table 10. Durability metrics comparison

Parameter	Traditional PEM	Novel PEM	Improvement (%)
Durability (hours)	800	1000	25

- Robust mechanical properties: The incorporation of PVDF in the membrane composition enhances its mechanical strength. This makes the membrane more resistant to physical wear and tear, thereby extending its operational lifespan.
- Stable performance over time: The novel PEM maintains consistent ionic conductivity and low hydrogen crossover rates over extended periods, ensuring stable performance and reducing the frequency of maintenance and replacements.

Table 10 compares the durability metrics of traditional PEMs with the novel PEM developed in this study, revealing a substantial 25% improvement in operational lifespan (from 800 to 1000 hours). This enhancement reflects the superior material properties and structural integrity of the novel PEM, which enable it to withstand the demanding operating conditions of fuel cells for extended periods. The durability of a PEM is a critical factor in determining the overall reliability and cost-effectiveness of a fuel cell system. The traditional PEM, with a lifespan of 800 hours, is limited by its susceptibility to chemical and mechanical degradation over time. Factors such as oxidative stress, high temperatures, and mechanical fatigue often lead to thinning, cracking, or loss of functionality in conventional membranes. In contrast, the novel PEM's advanced material composition and innovative structural design mitigate these issues, resulting in a 25% longer lifespan. The improved durability of the novel PEM is attributed to several factors. First, its superior resistance to chemical degradation, particularly from reactive oxygen species generated during fuel cell operation, ensures that the membrane remains intact and functional for a longer period. Second, the novel PEM's mechanical robustness allows it to endure repeated cycles of expansion and contraction caused by varying operating conditions, such as changes in humidity and temperature. These characteristics contribute to the membrane's ability to maintain its structural integrity and performance over an extended timeframe. The extended lifespan of the novel PEM also has significant practical implications. By reducing the frequency of maintenance and replacement, the novel PEM lowers the operational costs of the fuel cell system, improving its overall economic viability. Furthermore, the increased durability ensures more consistent performance,

enhancing the reliability of the fuel cell in real-world applications. This is particularly important for industries like transportation and stationary power generation, where uninterrupted operation is essential. The 25% improvement in durability demonstrated by the novel PEM represents a significant step forward in addressing one of the major limitations of traditional PEMs. Its enhanced chemical and mechanical stability not only increases the operational lifespan of the fuel cell but also contributes to its cost-effectiveness and reliability. These findings highlight the potential of the novel PEM to support the development of more sustainable and efficient fuel cell technologies.

The improvements in efficiency and durability of the novel PEM have synergistic effects on the overall performance of fuel cells:

- **Reduced operational costs:** Enhanced durability reduces the need for frequent maintenance and membrane replacement, lowering the total cost of ownership. The increased efficiency reduces fuel consumption, further contributing to cost savings.
- **Increased reliability:** The improved stability and longevity of the novel PEM ensure reliable performance over extended periods. This is particularly important for critical applications such as backup power systems and remote power supplies where reliability is paramount.
- **Broader applicability:** The enhanced performance of the novel PEM makes fuel cells more competitive for a wider range of applications, including automotive, stationary power generation, and portable power devices. This broader applicability can accelerate the adoption of fuel cell technology.

The novel PEM's contributions to efficiency and durability also have positive environmental implications:

- **Lower emissions:** Increased fuel efficiency leads to reduced hydrogen consumption and, consequently, lower emissions associated with hydrogen production. This aligns with global efforts to reduce greenhouse gas emissions and promote sustainable energy solutions.
- **Resource conservation:** The reduction in material degradation and the extended lifespan of the novel PEM contribute to resource conservation by minimizing waste and the need for frequent replacements.

The novel PEM significantly enhances the efficiency and durability of fuel cells. The improvements in ionic conductivity, reduced hydrogen crossover rates, and enhanced chemical and mechanical stability contribute to higher fuel cell efficiency and extended operational life. These advancements not only improve the performance and reliability of fuel cells but also reduce operational costs and environmental impact. The development of the novel PEM represents a crucial step forward in the quest for more sustainable and efficient hydrogen fuel cell technologies, offering promising prospects for a wide range of applications [52].

The novel PEM technology, with its enhanced ionic conductivity and reduced hydrogen crossover rates, has significant potential across various fuel cell applications. For portable fuel cells, the improved performance and durability of the membrane could lead to longer operating lifetimes and better efficiency in compact, low-power devices. In stationary fuel cells, the advancements in membrane technology could contribute to more reliable and cost-effective energy production for residential or industrial use. For automotive fuel cells, the novel PEM could enhance the fuel cell stack's efficiency, reducing the overall size and cost of the system while improving the vehicle's range. These applications highlight the broad impact of the developed PEM technology on diverse sectors.

5 Conclusion

This study has successfully demonstrated significant advancements in hydrogen fuel cell technology through the synthesis of novel Fe–N–C catalysts, supported by nanostructured carbon and integrated with an advanced PEM. The integration of these innovative components has resulted in substantial improvements in both fuel cell performance and durability, offering a promising path toward cost-effective and sustainable energy solutions. Key findings from this study include:

- A 19.88% increase in power density, reaching 0.85 W/cm^2, indicating a significant boost in fuel cell output.
- A 14.76% enhancement in operational stability, exceeding 1000 hours of continuous operation.
- Nanostructured carbon supports improved ORR activity by 30.13%, leading to more efficient catalytic processes.
- A 25.02% rise in current density, further enhancing overall fuel cell efficiency.
- The advanced PEM achieved a 20.00% increase in ionic conductivity, improving ion transport within the cell.
- A 25.00% increase in membrane durability, ensuring longer fuel cell life under challenging operational conditions.
- A remarkable 40.00% reduction in hydrogen crossover rates, contributing to an overall efficiency gain of 10.12%.

While the novel PEM shows significant improvements in performance, there are potential limitations that should be considered. One limitation is the durability of the membrane under long-term operation, particularly in high-stress environments such as automotive or industrial fuel cells, which may require further testing over extended periods. Additionally, the manufacturing process of the novel PEM, particularly the integration of PVDF and BMIM-BF_4, could pose challenges in terms of scalability and cost-effectiveness for large-scale production. Furthermore, while the reduction in hydrogen crossover is notable, further improvements may be needed to optimize the membrane for different fuel cell applications. These factors highlight the need for continued research and development to address these challenges and enhance the PEM's applicability.

Also, the environmental impact of the novel PEM is an important consideration in evaluating its sustainability. The use of PVDF and BMIM-BF_4 as materials may present environmental advantages, such as the potential for reduced environmental footprint compared to traditional materials, particularly if these materials are sourced responsibly and have a lower carbon footprint during production. However, the environmental drawbacks may include challenges related to the disposal of these materials at the end of the PEM's life cycle, as both PVDF and BMIM-BF_4 are synthetic polymers that may not be easily biodegradable. Additionally, the production of these materials could involve processes that contribute to greenhouse gas emissions if not managed properly.

These results underscore the potential of PGM-free catalysts and advanced membrane technologies to transform hydrogen fuel cell systems, making them more economically viable and

environmentally sustainable. To build upon these promising findings, future research can be focused on: (i) developing large-scale manufacturing processes for Fe–N–C catalysts and advanced PEMs to facilitate industrial adoption; (ii) exploring the integration of these fuel cells into real-world applications such as transportation, portable power units, and stationary power systems; (iii) conducting extended lifespan studies to further validate the long-term stability and reliability of these innovations under various environmental conditions; and (iv) investigating additional methods to lower production costs, making fuel cells more accessible for widespread use. By addressing these areas, future studies can continue to enhance the performance, affordability, and sustainability of hydrogen fuel cells, contributing to global energy transition efforts.

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Author contributions

Kairat A. Kuterbekov (Data curation [equal], Formal analysis [equal], Investigation [equal], Methodology [equal]), Kenzhebatyr Zh. Bekmyrza (Resources [equal], Software [equal], Validation [equal], Visualization [equal]), Asset M. Kabyshev (Conceptualization [equal], Methodology [equal], Software [equal], Writing—original draft [equal]), Marzhan M. Kubenova (Data curation [equal], Formal analysis [equal], Resources [equal], Supervision [equal], Writing—review & editing [equal]), Aliya Baratova (Conceptualization [equal], Methodology [equal], Validation [equal], Visualization [equal]), Iroda Abdullayeva (Data curation [equal], Methodology [equal], Resources [equal], Validation [equal]), and Abebe Temesgen Ayalew (Formal analysis [equal], Investigation [equal], Methodology [equal], Writing—original draft [equal], Writing—review & editing [equal]).

Conflict of interest

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