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Application of g-C_3N_4 in Low-Temperature Fuel Cell Technology: An Overview

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ABSTRACT

Particularly in low-temperature fuel cell applications, graphitic carbon nitride (g- C_3N_4) has attracted substantial interest due to its distinctive properties, including its exceptional thermal and chemical stability, adaptable electrical structure, and simplicity of synthesis. In this investigation, the function of g-C_3N_4 is investigated in a variety of low-temperature fuel cell systems, such as proton exchange membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFCs). Potential remedies to the constraints of conventional materials, including cost, durability, and activity, are provided by the incorporation of g-C_3N_4 as a catalyst support, co- catalyst, or membrane additive. g-C_3N_4 is a promising alternative for improving fuel cell efficacy due to its nitrogen-dense structure. Doping elements such as sulfur, phosphorus, and transition metals has significantly enhanced the performance of fuel cells. The following are included: improved power density, improved electrochemical stability, and increased resistance to fuel crossover. The potential of g-C_3N_4 to address cost and efficiency concerns in low-temperature fuel cells is investigated within the context of sustainable energy applications. The United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), are in alignment with these enhancements, as they underscore the development of energy conversion technologies that are both clean and efficient. Nevertheless, even with the promising results, additional research is required to fully understand the mechanisms that control the catalytic properties of g-C_3N_4 and to improve the synthesis of g- C_3N_4-based materials for commercial applications. In the development of next-generation low- temperature fuel cells, the recent progress and obstacles associated with g-C_3N_4 in fuel cell technology are analyzed in detail.

Keyword: g-C_3N_4; low-temperature fuel cells; proton exchange membrane fuel cells (PEMFCs); Sustainable Development Goals (SDGs); catalyst support

INTRODUCTION

Energy is essential in everyday living. The increased demand for energy is attributed to the country's fast-growing population and consistent rise in personal wealth. By 2035, an additional 1.6 billion individuals will necessitate energy, as projected by the global population, which is expected to exceed 8.7 billion (Senjyu & Howlader 2016). Concerns regarding the utilization of conventional fossil fuels and their impact on human health exist; nevertheless, the principal issue is the escalating demand for energy coupled with the diminishing supply of fossil fuels generated globally. As of the end of 2013, the renewable electricity capacity reached approximately 1560 GW, over double the 895 GW recorded at the beginning of 2004, according to a literature review (Bilgili et al. 2015). However, numerous disadvantages associated with renewable energy installations have been observed. The transportation of renewable energy is complicated by the frequent geographical distance between renewable power facilities and demand centres. The stability of grids in contemporary centralized power generation and distribution systems is significantly affected by the proliferation of dispersed renewable energy facilities, including wind farms and solar arrays. The curtailment strategy was employed to address these costly concerns and prevent their escalation. Alongside energy storage techniques, fuel cell technology is a recent advancement that offers a rapid resolution to the aforementioned issues. Fuel cells possess the capability to serve multiple applications, including portable electricity generation. The performance of fuel cells is influenced by various factors, including operating conditions (temperature, humidity, pressure), fuel cell design (application system and scale), and the composition of the polymer electrolyte within the fuel cell (Salleh et al. 2017).

The primary method of converting renewable energy is through fuel cell technology and other electrochemical reactions, potentially making it a viable strategy. The two most distinctive types of low-temperature fuel cells are Proton Exchange Membrane Fuel Cells (PEMFCs) and Direct Methanol Fuel Cells (DMFCs) (Qasem & Abdulrahman 2024). The solid polymer electrolyte employed in PEMFCs, which operate at temperatures ranging from 60°C to 80°C, facilitates proton mobility while impeding electron flow. This design is optimal for portable power systems and transportation applications due to its rapid startup periods and exceptional efficiency. DMFCs, a subtype of PEMFCs, directly utilize methanol as fuel, thereby eliminating the necessity for additional fuel refinement. Despite the fact that they are capable of achieving lower power densities, they can operate at temperatures that are comparable to those of PEMFCs. They are particularly advantageous for portable applications due to their effortless fuel storage and utilization. (Tellez-Cruz et al. 2021). The capacity of both varieties of fuel cells to directly convert chemical energy into electrical energy with minimal environmental impact is essential for the transition to sustainable energy systems.

Graphitic carbon nitride (g-C_3N_4) has attracted considerable attention in recent years as a result of its distinctive properties, which increase its potential for use in a variety of applications, such as fuel cell catalysis (Q. Wang et al. 2023)(Ghaemmaghami & Mohammadi 2019). The thermal and chemical stability of g-C_3N_4 are extraordinary, enabling it to endure adverse operational conditions without degradation. The long-term applications of fuel cells are contingent upon this stability. Electronic properties that are adjustable where various synthesis methods can be employed to customize the electronic properties of g-C_3N_4, which allows for optimization of specific catalytic processes. Its electron transfer reactions, which are indispensable for fuel cell operation, are efficiently facilitated by its bandgap of approximately 2.7 eV (Gao et al. 2022). The catalysticity of this substance g-C_3N_4 material has been identified as a potential catalyst material due to its non-toxicity and ability to improve reaction kinetics. Fuel cells' distinctive structure enables them to effectively facilitate the oxygen reduction reaction (ORR), a critical component of their operation. The objective of this work is to provide a comprehensive examination of the role of g-C_3N_4 in low-temperature fuel cells, with a particular emphasis on PEMFCs and DMFCs. The second section of the review concentrates on the potential of g-C_3N_4 to improve the durability and efficacy of fuel cell technology. The current review concentrates on the challenges and advancements associated with the utilisation of g-C_3N_4 in low-temperature fuel cells. This paper advocates for the transition to sustainable energy sources and provides a concise overview of the most recent advancements in g-C_3N_4 research.

OVERVIEW OF G-C_3N_4

The photocatalytic activity of graphitic carbon nitride (g-C_3N_4) is significantly influenced by the distinctive two-dimensional structure that comprises the carbon and nitrogen atoms (Tan et al. 2021). Understanding these characteristics is essential for optimizing the efficacy of g-C_3N_4 materials and customizing them for particular applications. At its core, g-C_3N_4 is composed of layered layers of nitrogen and carbon atoms that form a planar, hexagonal lattice. The term "graphitic" is derived from the

close resemblance between the layered structure and graphite. Weak van der Waals forces maintain the layers in place, and each layer is composed of tri-s-triazine (C_3N_3) units. The extensive surface area of g-C_3N_4 offers the potential for photocatalytic reactions and reactant adsorption, which are further facilitated by its layered structure. Consequently, it is an intriguing material for a variety of applications (Kumar et al. 2018).

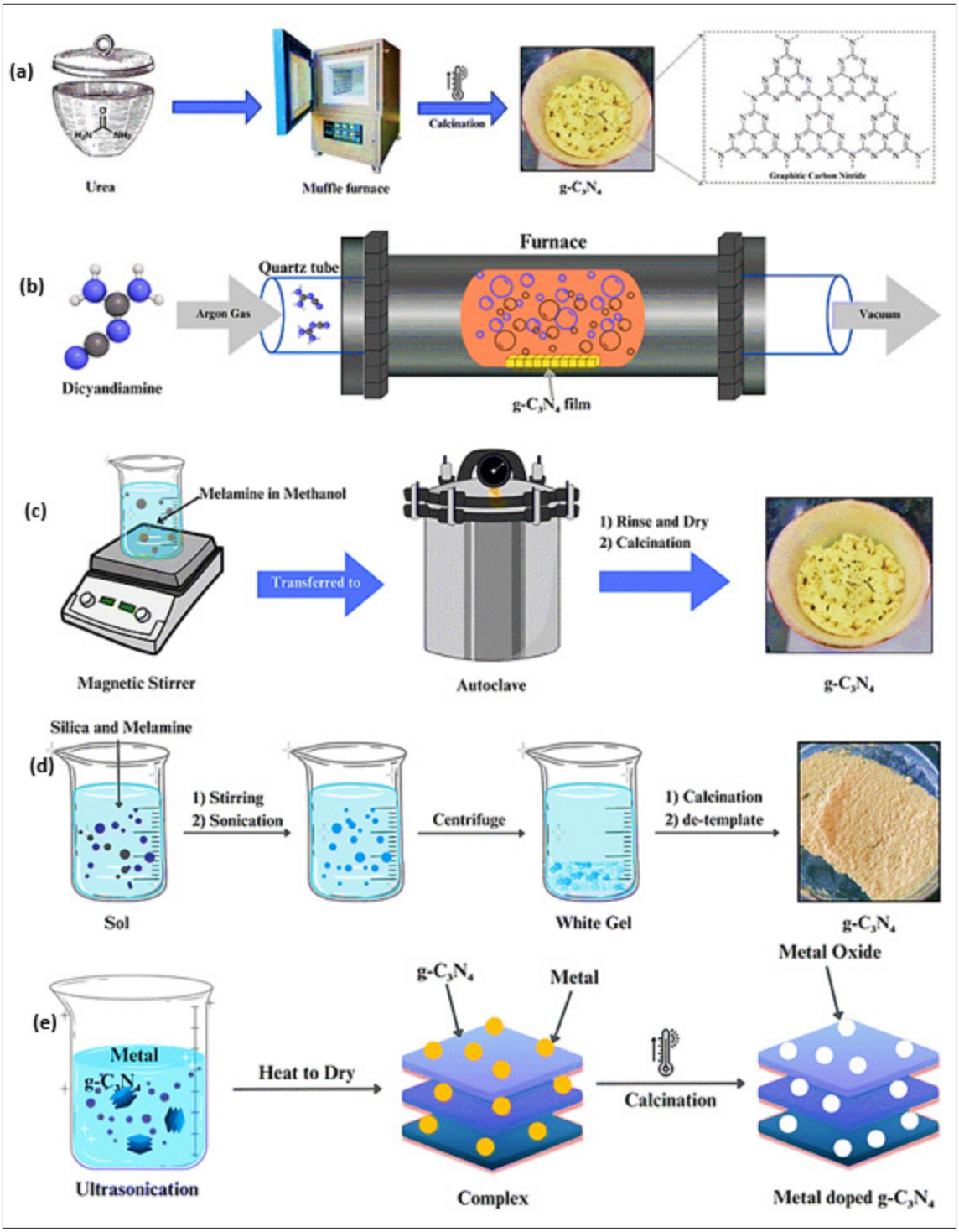

FIGURE 1. Schematic representation of the diverse synthesis methods used to produce graphitic carbon nitride (g-C_3N_4) and its substitutes (a) Calcination of urea in a muffle furnace. (b) Chemical vapor deposition (CVD) of g-C_3N_4 film using dicyandiamine. (c) Sol-gel method involving silica and melamine. (d) Hydrothermal synthesis of g-C_3N_4 using sol-gel method. (e) Synthesis of metal-doped g-C_3N_4 through ultrasonication and calcination

Graphitic carbon nitride (g-C_3N_4) has made substantial progress in its synthesis, allowing researchers to customise its properties for particular photocatalytic applications. Various synthesis methods are examined in this document, with a focus on their respective advantages and disadvantages. Thermal polymerisation of cheap precursors, including melamine, urea, cyanamide, dicyanamide, thiourea, and cyanuric acid, is a frequently employed method for the production of g-C_3N_4. During this procedure, the precursors are typically heated to moderate temperatures (approximately 500–600 °C) in inert gas atmospheres. Figure 2(a) illustrates the pertinent data. The thermal polymerisation process generates a layered g-C_3N_4 structure that is distinguished by its large surface area, rendering it suitable for a diverse array of photocatalytic applications. Due to its affordability and simplicity, the procedure has gained popularity. Through the synthesis of g-C_3N_4, CVD provides a method for precisely regulating the material's thickness and shape. The process of chemical vapour deposition (CVD) in a high-temperature reactor is illustrated in Figure 2(b). Volatile precursors, including cyanamide, are introduced. As these precursors decompose, substrates are coated with g-C_3N_4. This technique enables the creation of nanostructures and thin coatings that are suitable for use in optoelectronics and photovoltaics. Specialized equipment is frequently required for CVD, which is frequently associated with increased production costs (Chebanenko et al. 2022)(Chubenko et al. 2022). Thermal polymerisation of cheap precursors, including melamine, urea, cyanamide, dicyanamide, thiourea, and cyanuric acid, is a frequently employed method for the production of g-C_3N_4. During this procedure, the precursors are typically heated to moderate temperatures (approximately 500–600 °C) in inert gas atmospheres. Fig. 2(a) illustrates the pertinent data. The thermal polymerisation process generates a layered g-C_3N_4 structure that is distinguished by its large surface area, rendering it suitable for a diverse array of photocatalytic applications. Due to its affordability and simplicity, the procedure has gained popularity. Through the synthesis of g-C_3N_4, CVD provides a method for precisely regulating the material's thickness and shape. The process of chemical vapour deposition (CVD) in a high-temperature reactor is illustrated in Figure 2(b). Volatile precursors, including cyanamide, are introduced. As these precursors decompose, substrates are coated with g-C_3N_4 (Kuldeep et al. 2021)(Kunhikrishnan et al. 2023). Carbonaceous materials or mesoporous silica are employed as templates in the "template-assisted synthesis" method to facilitate the development of g-C_3N_4 with precise structures. Please see Figure 2(d). It is possible to modulate the surface area and porosity of g-C_3N_4 by employing templates with specific pore diameters and shapes, which are critical factors that influence its photocatalytic performance. This method facilitates the development of g-C_3N_4 materials with precisely adjusted characteristics for applications such as the elimination of pollutants and the transformation of solar energy (Hao et al. 2020). The study of doping and co-doping with elements such as sulphur, boron, and metals has enhanced the photocatalytic activity of g-C_3N_4, as illustrated in Figure 2(e). Doping alters the electronic structure of the g-C_3N_4 lattice and introduces impurities, thereby increasing the number of active sites for photocatalytic processes. Co-doping is the mechanism by which numerous elements are introduced simultaneously in an effort to generate synergistic effects. In a diverse array of photocatalytic reactions, the techniques significantly enhance the selectivity and efficiency of g-C_3N_4 (Bui et al. 2020)(Jiang et al. 2020).

G-C_3N_4 AS A CATALYST IN FUEL CELLS

CATALYTIC ACTIVITY IN OXYGEN REDUCTION REACTION (ORR)

The structural properties of g-C_3N_4, modification techniques, and the combination of single-atom catalysts are among the critical factors that contribute to its improved efficacy in facilitating the oxygen reduction process (ORR) in low-temperature fuel cells. Yan Wang and his colleagues devised high-efficiency Fe/N-doped carbon catalysts for oxygen reduction from graphite phase carbon nitride (Yan Wang et al. 2024). Purposes of fabrication After the pyrolysis of melamine to produce the g-C_3N_4, FeCl3 is introduced to the Fe-NC catalyst. Due to its structural characteristics and effective FeCl3 enrichment, g-C_3N_4 can catalyse the oxygen reduction reaction (ORR) more efficiently. This also improves electron transport and catalytic performance. Zhu et al. (Zhu et al. 2023) examine the improvement of the catalytic activity and selectivity of enzyme-mimicking single-atom catalysts for the oxygen reduction process. These catalysts are distinguished by the integration of pyrrole-type M-N_4 sites into g-C_3N_4. Employing the methodology Methods of density functional theory for the evaluation of catalyst stability and adsorption behavior, with a focus on catalytic activity. The stability of embedded M-N4 sites and the advantageous adsorption characteristics of reaction products are the reasons for the increased activity of g-C_3N_4 in the oxygen reduction reaction (ORR). Consequently, the catalytic selectivity and efficiency are enhanced. Niu and his crew (Niu et al. 2020) Ensure that the source of the oxygen reduction reaction activity in single atoms supported on g-C3N4 monolayers is investigated using a first-principles approach. An

electronic structure analysis and charge transfer approach are employed to investigate the oxygen reduction reaction (ORR) using first-principles calculations. The d-band center, ICOHP, the energy descriptor ΔE*OH, and the charge transfer from transition metal atoms to g-C_3N_4 are all critical components that collaborate to enhance ORR activity. Zheng et al. (Zheng et al. 2017) introduced a new class of electrocatalysts for oxygen electrode reactions, specifically Molecule-Level g-C_3N_4 coordinated transition metals. The theoretical evaluation of the cobalt–C_3N_4 catalyst is the method employed in this development. Validation of electrocatalytic activity through experimental methodologies. g-C_3N_4's substantial activity in the oxygen reduction reaction (ORR) is ascribed to the precise coordination of M–N_2 within its structure, which enhances electrocatalytic performance to levels that are comparable to precious metal standards in alkaline environments. In the oxygen reduction reaction (ORR), the high catalytic activity of g-C_3N_4 is predominantly due to its unique structural properties, the integration of single-atom catalysts, and the use of efficient doping methods. In the g-C_3N_4 matrix, these factors jointly promote favorable adsorption behavior, enhance electron transfer, and facilitate precision metal coordination. Multiple studies have demonstrated that g-C_3N_4-based catalysts exhibit superior ORR performance in specific applications when contrasted with conventional platinum-based catalysts. There is significant potential for the advancement of the development of sustainable and efficient energy storage and conversion devices through additional research and optimization of these materials.

METAL-FREE CATALYSTS

Two-dimensional graphitic carbon nitrides (g-CNs) are among the most intriguing metal-free catalysts. Their unique electrical, chemical, and mechanical properties are associated with the high nitrogen content that is systematically organized within the carbon framework. The exceptional physico-chemical properties of the g-CNs, which include the capacity to adjust their band gaps and their exceptional thermal, chemical, and mechanical stability, render them suitable for a diverse array of applications. Deng and his colleagues (Deng et al. 2024) current focus of research is on the Metal-Free Modification that Overcomes the Photocatalytic Limitations of Graphitic Carbon Nitride Effective Generation and In Situ Use of Hydrogen Peroxide. This investigation emphasises the enhanced efficacy of g-C_3N_4 in the production of H2O2, with an emphasis on its potential applications in water filtering and organic synthesis. By eliminating the use of precious metals and preventing heavy metal discharge, metal-free modification enhances the stability and performance of g-C_3N_4, resulting in greater environmental sustainability and enhanced photocatalytic efficiency in fuel cell applications. Research conducted by Oliveira et al. (Oliveira et al. 2023) catalytic characteristics and mechanism of a novel heterogeneous Fenton-like catalyst that utilizes g-C_3N_4 functionalized with cyamelurate-like group as a metal-free catalyst. The research demonstrated that catalysts manifested Fenton-like characteristics by generating hydroxyl radicals, with performance being dependent on pH levels and functional groups. Harun and his colleagues (Harun et al. 2022) investigated the advancements of carbon-based material composites and g-C_3N_4 in fuel cell applications. The review analyzes the performance of fuel cells and associated systems by examining g-C_3N_4 and carbon-based materials that enhance fuel cell performance. It also offers insights for the enhancement of fuel cells. The stability and efficacy of g-C_3N_4 in fuel cells are improved by the absence of metal, which reduces total costs and increases durability by enhancing electrochemical activity and mitigating corrosion hazards. Yang and colleagues (Yang et al. 2023) conducted a study on metal-free carbon catalysts that are extremely active and durable for anion-exchange membrane fuel cells. The investigation reveals that the NDPC-1000 exhibits a robust overall response rate (ORR) activity and endurance, as evidenced by a maximal power density of 913 mW cm^{-2}. Graphitic carbon nitride was synthesized by Prabakaran et al. (Prabakaran et al. 2021) for fuel cell applications. The development emphasizes the importance of g-C_3N_4 in fuel cell applications by addressing its synthesis and modifications. Ultimately, the chemical inertness and thermal stability of g-C_3N_4 are improved by the absence of metal, making it suitable for fuel cell applications, despite its subpar electrical conductivity.

APPLICATIONS IN DIFFERENT FUEL CELL TECHNOLOGIES

PROTON EXCHANGE MEMBRANE FUEL CELLS (PEMFCS)

Graphitic carbon nitride (g-C_3N_4) is incorporated into proton exchange membrane fuel cells (PEMFCs) to significantly reduce production and operating costs by enhancing performance and reducing dependence on precious metals. Akyüz et al. (Akyüz & Demirbaş 2024) identified g- C_3N_4/polymeric metallophthalocyanine as a novel electrocatalyst. According to the investigation, the electrocatalytic activity of g-C_3N_4/Poly-NiPc is exceptional, as its current density is nearly 100 times that of g-C_3N_4. A number of critical issues must be addressed in order to

optimize g-C_3N_4 for real-world applications in proton exchange membrane fuel cells (PEMFCs). Main objectives of these challenges include enhancing its catalytic activity and stability. Ma et al. (Ma et al. 2024) have determined that the Pure g-C_3N_4 exhibits restricted catalytic activity as a result of rapid recombination and inadequate charge carrier separation, which impedes its efficacy in PEMFC applications. Based on the investigation, the photocatalytic evolution of hydrogen may be enhanced by g-C_3N_4. In addition, methodologies were identified for enhancing the photocatalytic activity of g-C_3N_4. Defective g-C_3N_4 was developed by Zhang and associates (Zhang et al. 2023) [30] to enhance the efficiency of high-temperature proton exchange membrane fuel cells by optimizing the phosphate distribution in the catalytic layer. Improved phosphoric acid dispersion in the catalytic layer of g-C_3N_4 leads to increased intrinsic reactivity and catalyst durability. The platinum concentration is reduced to 0.20 mgPt cm^{-2}, which enables the attainment of high-power densities (672 mW cm^{-2}). The Engineering g-C_3N_4 composited Fe-UIO-66 was developed by An and colleagues (An et al. 2022) to in-situ generate robust single-atom Fe sites for high-performance PEMFC and Zn-air batteries. Study findings High performance was achieved in the PEMFC and Zn-air battery, and an effective electrocatalyst for the oxygen reduction reaction was invented. The photo/electrocatalytic hydrogen evolution was conducted by Mehtab et al. (Mehtab et al. 2023) using Type-II Cu_2O/g-C_3N_4. Heterostructure: The high charge transport efficacy is addressed by density functional theory. Discovery In comparison to g-C_3N_4, the overpotential for HER and OER is lower, and the photocatalytic hydrogen evolution rate is higher at 3492 µmol $gcat^{-1}$. heterostructures: The combination of g-C_3N_4 and Cu_2O enhances overall efficiency by reducing overpotentials for hydrogen evolution processes and improving charge transfer. Before this technology can be implemented in practice, it is necessary to address concerns such as charge carrier separation and stability, despite the fact that g-C_3N_4 can enhance the catalytic performance of PEMFCs. The development of energy conversion technologies that are more sustainable and efficient will be facilitated by this.

DIRECT METHANOL FUEL CELLS (DMFCS)

The unique structural and chemical properties of g-C_3N_4 are responsible for the improvement of methanol oxidation in direct methanol fuel cells (DMFCs), thereby enabling improved catalyst performance. The mechanisms that are at play are clarified in the following points: Platinum (Pt) nanoparticles are effectively supported by g-C_3N_4, which enhances their stability and dispersion. The catalytic activity is increased as a result of the enhanced interaction between Pt and the support created by the presence of nitrogen species in g-C_3N_4 (Liang et al. 2021). The anchoring of Pt nanoparticles is further facilitated by the hydroxyl groups that are introduced on the surface of g-C3N4, which also accelerates the oxidation of carbon monoxide (CO), a common intermediate in methanol oxidation (Liang et al. 2022). Shen and colleagues (Shen et al. 2022) assessed the characterization of Pt/g-C_3N_4-catalyzed methanol oxidation for the purpose of driving peroxygenase-catalyzed oxyfunctionalization of hydrocarbons. Fabrication method employs photocatalysis with Pt/ g-C_3N_4 to generate H_2O_2 and conduct a mechanistic investigation using UV–vis and DFT calculations. The results were evaluated by Form, which obtained a turnover number of 133,000, which is four times higher than unsupported g-C_3N_4, and hydroxylation of C–H bonds with up to 99% enantiomeric excess. For the electrocatalytic oxidation of methanol, Liang and his team [33] investigated the substantial promotion of g-C_3N_4 on the Pt/CNS catalyst. The research determined that g- C_3N_4 substantially improves the electrocatalytic performance of the Pt/CNS catalyst and enhances methanol oxidation. Bai and his collaborator (Bai et al. 2021) developed the construction of a Pt/g-C_3N_4/SiC heterostructure for enhanced methanol photoelectrooxidation. The methodology employed in this investigation UV-Vis spectroscopy characterization and annealing at 550°C for varying durations. In comparison to other catalysts, the Pt/g-C_3N_4/SiC-90 results indicate a higher photoelectrocatalytic current density. Additionally, the catalyst demonstrates long-term stability. The material g-C_3N_4, which is present in methanol fuel cells, is a promising candidate for fuel cell technology. It enhances methanol oxidation by providing a supportive matrix for platinum nanoparticles, reducing deleterious effects, and enhancing catalytic acti.

CHALLENGES AND FUTURE DIRECTIONS

\In spite of its substantial potential, graphitic carbon nitride (g-C_3N_4) is not extensively utilised in low-temperature fuel cells such as Direct Methanol Fuel Cells (DMFCs) and Proton Exchange Membrane Fuel Cells (PEMFCs) due to numerous impediments. The subsequent items are recorded in Table 1. Scalability is indispensable. The bulk production of high-quality g-C_3N_4 materials presents a significant challenge. The synthesis of g-C_3N_4 frequently impedes large-scale production due to the necessity of specific conditions, such as high temperatures and

specialized chemical treatments (Qamar et al. 2023). Another obstacle is the maintenance of consistent and homogeneous material properties, including particle size and surface area, across the samples. The durability of fuel cells may be impacted by the variable pressures, temperatures, and chemical exposures that are frequently present in extreme environments. In order to enhance the durability of g-C_3N_4 under these circumstances, substantial improvements are required. The risk of structural degradation as a result of protracted exposure to fuel cell operating conditions restricts the extended application of g-C_3N_4 (Rashidi et al. 2022)(Yun Wang et al. 2020). g-C_3N_4 exhibits catalytic efficacy that is still inferior to that of conventional platinum-based catalysts, despite its nitrogen-rich structure and high surface area. Particularly in order to enhance these properties, additional consideration is required to optimize the electron transport capabilities and surface reactivity of g-C_3N_4. The current catalytic activity of g-C_3N_4 is insufficient; therefore, it is imperative to enhance its properties by doping or integrating it with other nanomaterials. Despite its nitrogen-rich composition and extensive surface area, the catalytic performance of g-C_3N_4 is suboptimal in comparison to conventional platinum-based catalysts. Additional refinement is necessary to enhance the surface reactivity and electron transport characteristics of g-C_3N_4. In order to enhance its properties, g-C_3N_4 must be doped or integrated with other nanomaterials, as it currently demonstrates insufficient catalytic activity.

Innovative synthesis techniques should be the primary focus of future research in order to resolve the identified constraints. By investigating alternative and more efficient synthesis methods, such as hydrothermal methods, chemical vapor deposition (CVD), and sol-gel processes, it may be possible to enhance the control over the structural properties of g-C_3N_4, thereby facilitating mass production (Kumari et al. 2023). These techniques enable the development of customized applications for a variety of fuel cell types by precisely modifying surface properties. The catalytic performance and durability of the g-C_3N_4 framework have been significantly improved through the use of sophisticated doping methods through the integration of transition metals (e.g., Fe, Co, Ni) and non-metals (e.g., S, P, B). Further research should focus on the multi-elemental modification of g-C_3N_4 to improve its chemical and physical properties. In addition to enhancing the efficiency of the oxygen reduction reaction (ORR), these strategies could also enhance corrosion resistance and electron mobility. Another aspect is the integration of supplementary nanomaterials, which g-C_3N_4 has the potential to improve fuel cell performance by forming synergistic interactions with a variety of carbon-based materials, such as graphene and carbon nanotubes, as well as metal oxides (Özmen et al. 2021). Graphene/g-C_3N_4 hybrids are highly attractive candidates for advanced fuel cell electrodes due to their enhanced electron transport and durability. Their synergistic properties have the potential to enhance performance optimization and cost efficiency, making nanocomposite materials a significant field for future exploration (Kausar et al. 2023) (Dey et al. 2024) (Osman et al. 2021).

TABLE 1. Challenges and potential solutions for g-C_3N_4 in energy applications

Challenges/Properties	Current g-C_3N_4-Based Solutions	Potential Future Solutions
Scalability	Small-scale batch production	Sol-gel/CVD methods for large-scale synthesis
Durability	Degradation in long-term operations	Multi-elemental doping to enhance stability
Optimization of Catalytic Activity	Moderate catalytic activity in PEMFCs & DMFCs	Advanced doping and integration with nanomaterials
Cost	Lower than platinum-based catalysts	Further reduction via enhanced synthesis techniques
Fuel Crossover Resistance	Moderate resistance in DMFC applications	Improved via composite materials (e.g., graphene/g-C_3N_4)
Power Density	10-15% improvement with basic g-C_3N_4	>25% improvement with doped or hybrid materials

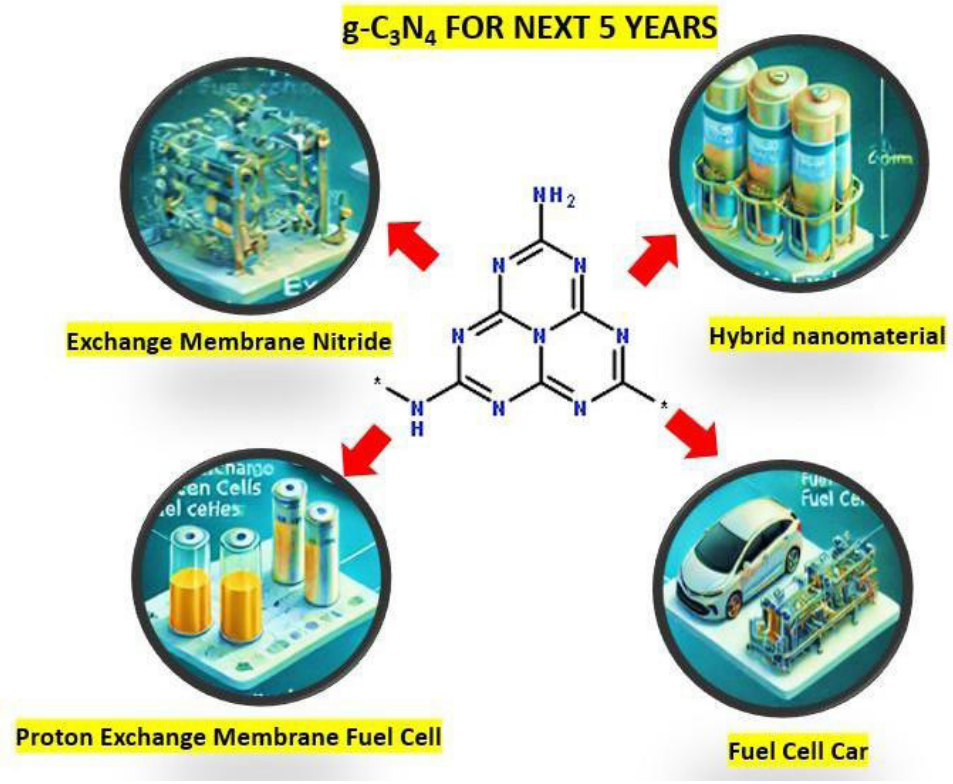

FIGURE 2. Powering the future with g-C_3N_4

The future prospects of g-C_3N_4 in fuel cell applications that it is anticipated that g-C_3N_4 will be instrumental in the advancement of fuel cell technology that is both cost-effective and high- performing within the next five years. It is anticipated that the development of innovative synthesis methods and doping strategies will significantly influence the potential for portable power applications and renewable energy storage solutions. The expanding significance of composite materials and hybrid systems in the attainment of ISO standards for fuel cells, including ISO 14687-2 (which specifies the hydrogen fuel purity for PEM fuel cells) and ISO 22734 (for hydrogen generators that utilize water electrolysis), can be effectively illustrated through a graphical representation of anticipated advancements in g-C_3N_4. The standards that have been established will facilitate the alignment of upcoming technological advancements with international objectives, such as Malaysia's National Energy Transition Roadmap (NETR), which prioritizes sustainable development through the implementation of green energy solutions.

CONCLUSION

Graphitic carbon nitride (g-C_3N_4) is a prospective candidate for low-temperature fuel cell technology due to its unique characteristics, which include its elevated thermal and chemical stability, adaptable electronic structure, and simplified synthesis. This technology's ability to transcend the limitations of conventional materials is demonstrated by its implementation in fuel cells, such as Direct Methanol Fuel Cells (DMFCs) and Proton Exchange Membrane Fuel Cells (PEMFCs). g-C_3N_4 significantly enhances fuel cell performance, particularly in the areas of power density, electrochemical stability, and fuel crossover resistance, when acting as a catalyst support, co-catalyst, or membrane addition. Sulfur, phosphorus, and transition metals are incorporated to further enhance the catalytic properties of the substance. Additionally, g- C_3N_4 is in accordance with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), which emphasizes its potential to provide sustainable energy solutions. Yet, despite the optimistic prognosis, additional research is required to fully elucidate the catalytic mechanisms and to optimize the production of g-C_3N_4 for widespread commercial use. The development of next-generation fuel cells for a more sustainable energy future is contingent upon the ongoing obstacles and advancements with respect to g-C_3N_4.

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DECLARATION OF COMPETING INTEREST

None.

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