



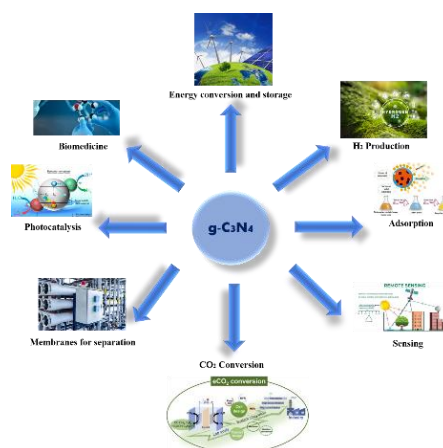
GRAPHITIC CARBON NITRIDE: PAVING THE WAY FOR REVOLUTIONARY BIOMEDICAL AND NANO LANDSCAPES IN THE LAST DECADE

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In this review, we analyzed research articles published in the last decade that explore the applications of graphitic carbon nitride ($g\text{-C}_3\text{N}_4$). $g\text{-C}_3\text{N}_4$ is a highly versatile nanomaterial attracting significant attention in the medical and technology fields. In the medical domain, $g\text{-C}_3\text{N}_4$ exhibits promising potential in diverse areas such as biomedical applications, wound healing, anti-cancer drug coating, tissue engineering, and antimicrobial activities. Furthermore, $g\text{-C}_3\text{N}_4$ can enhance the efficacy of conventional drugs, opening up new avenues for treating infections and improving wound healing processes. In advanced nanotechnology, $g\text{-C}_3\text{N}_4$ is an exceptional material for photocatalysis, energy conversion, sensors, and modern batteries. Its unique properties enable remarkable advancements in these fields, contributing to developing efficient and sustainable technologies. The article discusses the latest applications of $g\text{-C}_3\text{N}_4$ in a range of fields, such as biomedicine, nanosensors, tissue engineering, nanomaterials, anticancer, photocatalyst, and modern batteries. It also addresses the challenges faced in researching $g\text{-C}_3\text{N}_4$ and presents future perspectives on the topic. This evaluation aims to help readers assess the current status of $g\text{-C}_3\text{N}_4$ and its potential for future development.



INTRODUCTION

Graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) is a two-dimensional nanomaterial made up of carbon and nitrogen atoms arranged in a hexagonal lattice structure.^{1,2} Its chemical composition can be represented by the formula “C” for carbon and “N” for nitrogen.^{3–5} This material has been attracting considerable interest in recent years due to its low cost and high performance, making it an intriguing candidate for various energy-related applications.^{6,7} With its unique physical characteristics, $g\text{-C}_3\text{N}_4$

holds the potential for utilization in catalysis, solar energy, and optoelectronics.^{8,9}

In the realm of medical applications, $g\text{-C}_3\text{N}_4$ exhibits a wide range of biological activities, including wound healing, cancer therapy, and drug delivery.^{10–13} It possesses exceptional physical and chemical properties, such as biocompatibility, low toxicity, and strong photocatalytic activity.^{14–16} Moreover, $g\text{-C}_3\text{N}_4$ has demonstrated the ability to enhance the antimicrobial properties of conventional drugs, improving their efficacy in treating infections¹¹. Its controllable band gaps,

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facile functionalization, high thermal stability, and nano-composition with heteroatoms further enhance its importance in various fields.^{17,18} The fluorescent features and optical transparency of g-C₃N₄ enable its application in biomedical areas such as biosensing, antimicrobial treatments, and photodynamic diagnosis.^{15,19,20}

In energy conversion, g-C₃N₄ is employed as a photo-anodic material in dye-sensitized solar cells, displaying high efficiency in mass-energy conversion.^{21,22} It is also used for the purification of water and air, removing organic pollutants and volatile organic compounds, respectively.²³ Furthermore, g-C₃N₄ has applications in environmental remediation by effectively removing heavy metal ions from contaminated soils and water.^{24,25} Additionally, g-C₃N₄ can be used as a cathode material for lithium-ion batteries, enhancing their performance and stability.^{3,26} As the research data on g-C₃N₄ materials continues to grow, there is an urgent need for a comprehensive review. This study aims to summarize the encapsulated applications of g-C₃N₄ in both nanotechnology and biomedicine.

METHODOLOGY

This review examines the advancements and applications of graphitic carbon nitride (g-C₃N₄) across various domains, including drug delivery, biomedical applications, and sensor technology, based on studies published between 2014 and 2024. A comprehensive search strategy was employed using databases such as PubMed, ScienceDirect, Google Scholar, Scopus, IEEE Xplore, and SpringerLink. Relevant keywords, including “g-C₃N₄”, “drug delivery”, “biosensors”, and “biomedical applications”, were used to retrieve peer-reviewed articles, conference papers, and experimental studies. The selection criteria focused on studies that evaluated the properties, synthesis, and applications of g-C₃N₄, with exclusion of research published before 2014 or that did not provide substantial scientific data. Data extraction involved reviewing material synthesis methods, key properties of g-C₃N₄, and its application in various technologies. The quality of included studies was assessed based on experimental rigor, validity of results, and reporting of safety evaluations, especially in biomedical contexts. Through this

methodology, the review synthesizes current knowledge on g-C₃N₄'s potential, identifies trends and gaps in research, and offers insights into future directions for its application in nanotechnology and biomedicine.

APPLICATIONS

With its versatility and promising properties, graphitic carbon nitride (g-C₃N₄) holds great potential for advancements in a wide range of fields, including medical and nanotechnology applications. Here we are discussing thrilling uses of g-C₃N₄ in these areas:

Medical Applications

Anticancer and antimicrobial activities: g-C₃N₄ demonstrates exceptional potential as a photosensitizer in photodynamic therapy, providing a promising approach to cancer treatment. Upon exposure to suitable wavelength light, g-C₃N₄ generates reactive oxygen species (ROS), selectively targeting and destroying cancer cells while preserving healthy tissues.

Antibacterial coating: Unique structure and surface properties of g-C₃N₄ make it an ideal candidate for antibacterial coatings. These coatings effectively inhibit bacterial growth, providing robust control and prevention of infections. This is particularly crucial for implanted devices such as prosthetics and catheters, which are prone to infections.

Tissue Engineering: It can be incorporated into various scaffolds, creating versatile nanomaterials suitable for tissue engineering applications. It offers mechanical support and facilitates cell adhesion, creating a favorable microenvironment for proper cell growth and tissue regeneration.

Nanotechnology Applications:

Energy Storage batteries: With its robust electronic structure and high surface area, g-C₃N₄ holds significant potential as an electrode nanomaterial in energy storage devices such as supercapacitors and modern Li-ion batteries. Its unique properties contribute to enhanced energy storage performance and electrochemical reactions.

Photocatalysis: It exhibits remarkable photocatalytic properties, making it highly valuable for environmental remediation applications. When exposed to sunlight, it efficiently degrades organic pollutants and removes contaminants from water and air, supporting the purification of these vital resources.

Sensors: Given the increasing demand for electrical and optically active nanomaterials, g-C₃N₄ is a versatile sensing material in nanosensors. It demonstrates sensitive and selective detection capabilities for various analytes, including heavy metals, volatile organic compounds, and biomolecules. Its utilization in environmental and biomedical applications is instrumental in sensing and monitoring these substances.

These are just examples of the diverse range of applications of graphitic carbon nitride in medicine and nanotechnology. The unique properties of g-C₃N₄ continue to drive innovative research and contribute to advancements in various fields.^{27,28}

DERIVATIVIZATION OF g-C₃N₄

Recent advancements in the derivatization of g-C₃N₄ placed significant emphasis on enhancing chemical properties and synthesis methods to

unlock the full potential of this material in various technologies²⁹. Achieving cost-effective and large-scale production of g-C₃N₄ is a critical aspect of its synthesis. Several approaches were explored for the preparation of g-C₃N₄ derivatives, including solution-based synthesis, thermal decomposition, photothermal methods, laser-based heating, and hydrothermal methods.³⁰ Notably, g-C₃N₄ and its derivatives show promising results in augmenting the efficacy of conventional drugs for the treatment of malignant infections.³¹ As a well-known polymeric and organic-based nanomaterial, g-C₃N₄ consists of nitrogen and carbon atoms arranged in an alternating pattern within the aromatic ring structure of g-C₃N₄ (the basic units can be observed in Fig. 1). Furthermore, various functionalized forms of g-C₃N₄ were developed, as depicted in Fig. 2. These derivatives attracted tremendous attention, particularly in the field of water splitting through photocatalytic action.

The continuous exploration and refinement of g-C₃N₄ and its derivatives hold significant promises for advancing technologies in several domains, opening up new opportunities for innovative applications.^{32,33}

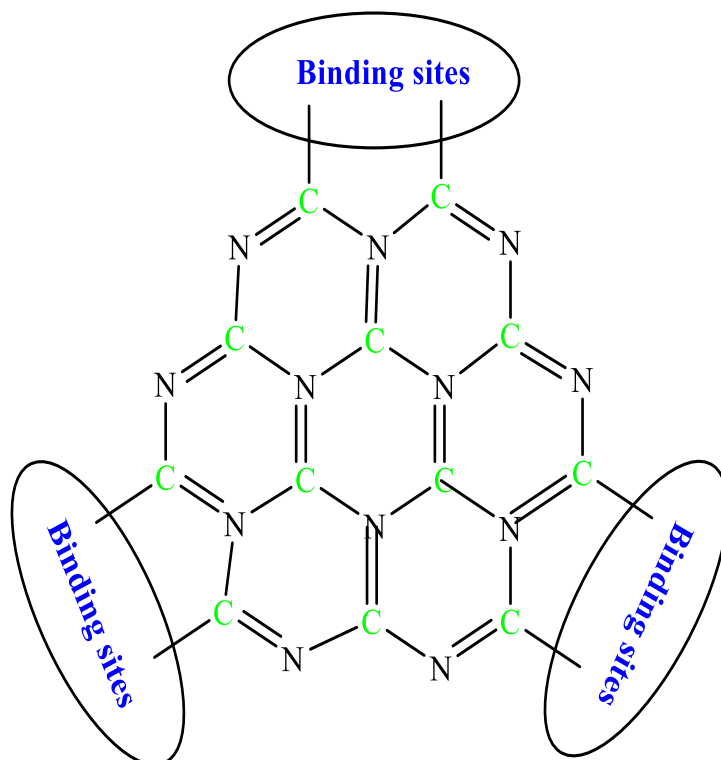


Fig. 1 – Proposed molecular structure of g-C₃N₄.³⁴

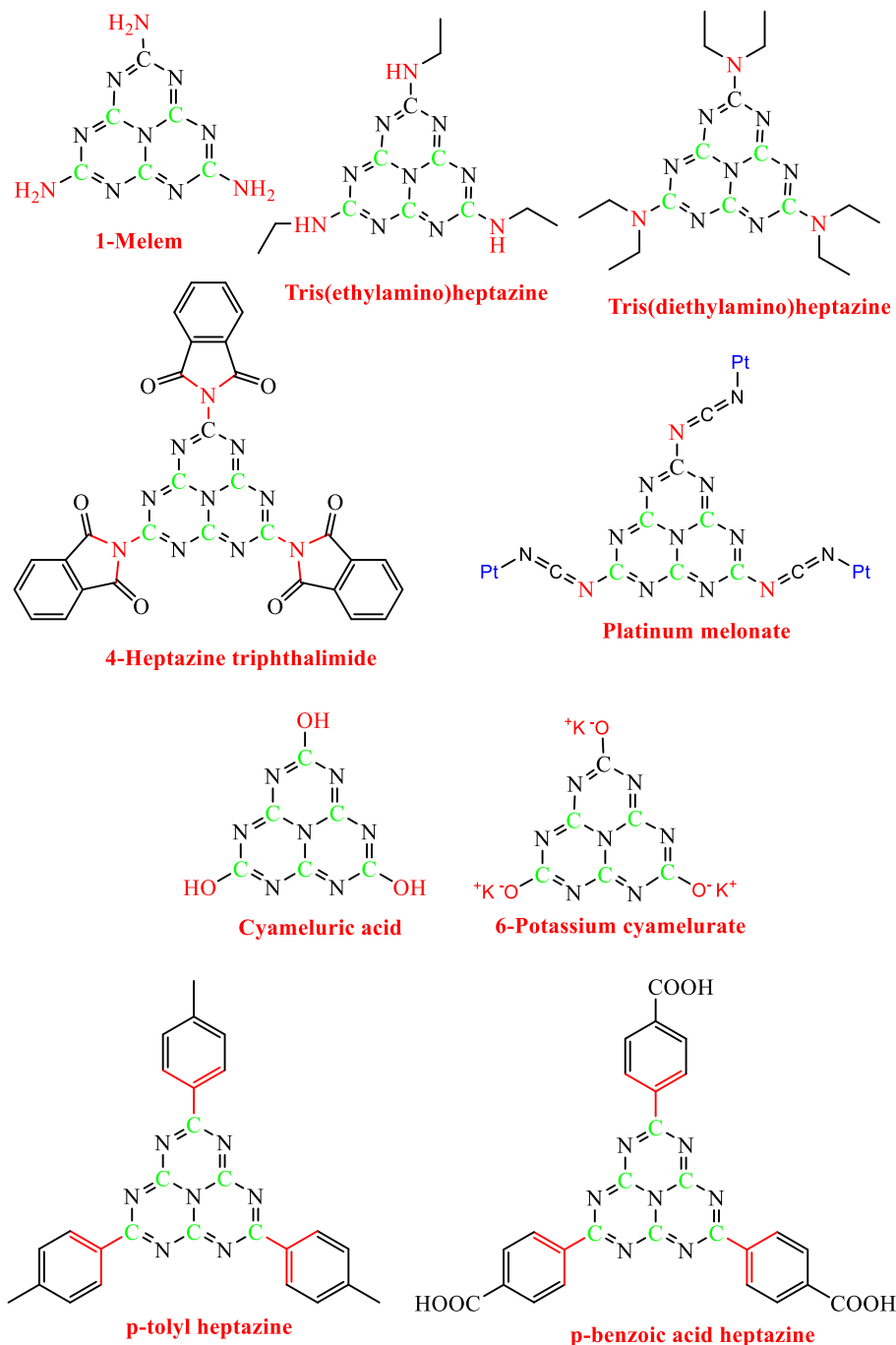


Fig. 2 – Proposed structures of functionalized g-C₃N₄, highlighting the introduction of various functional groups for tailored properties.³⁵

CATALYSIS

Cao *et al.* (2015) highlighted advancements in g-C₃N₄-based catalysts, showcasing their versatility in photocatalytic applications such as organic synthesis, water splitting, pollutant degradation, CO₂ reduction, and bacterial disinfection. Through atomic-level doping (*e.g.*, with sulfur, phosphorus, or nitrogen), molecular modifications, and heterojunction formations with semiconductors like

TiO₂, these catalysts demonstrated improved efficiency and selectivity. Enhanced hydrogen evolution rates (50–120 μmol h⁻¹), pollutant degradation efficiencies (up to 95%), and CO₂ reduction yields (10–30 μmol g⁻¹ h⁻¹) were achieved under visible light. Additionally, modifications such as surface exfoliation or Ag nanoparticle incorporation improved ROS generation, enabling bacterial inactivation rates exceeding 90% within an hour. These innovations underline the potential of

g-C₃N₄ in addressing critical energy and environmental challenges.

Hayat *et al.* (2022) highlighted recent advancements in the field of visible-light-driven g-C₃N₄ photocatalysts and their applications in environmental and chemical processes. Additionally, g-C₃N₄ holds significant potential as a valuable resource and proposes its utilization for the development of efficient and highly stable photocatalysts. This underscores the material's growing relevance in sustainable technologies, providing a robust platform for innovation in clean energy and environmental remediation.

g-C₃N₄-based nanocomposites were recently reviewed³⁶. The unique features of g-C₃N₄, such as p-n junctions, photosensitization, schottky junctions, surface plasmon resonance effects, and superconductivity recently reviewed.⁵ These studies demonstrated the enhanced performance of g-C₃N₄ in various energetic and environmental applications, including pollutant degradation, photocatalytic H₂ generation, CO₂ reduction, disinfection, and supercapacitors.^{37,38} It's fascinating to see how these structural and electronic properties have been tailored to optimize performance across such diverse applications, reflecting the adaptability of g-C₃N₄-based materials. This is a remarkable example of how compositional tuning can significantly amplify the catalytic performance, paving the way for sustainable energy solutions through CO₂ utilization.

The photocatalytic activities of some composites, namely Ag₃PO₄/g-C₃N₄, were intensively studied. Some researchers successfully synthesized Ag₃PO₄ salt on the surface of g-C₃N₄ using in situ methods, resulting in the formation of Ag₃PO₄/g-C₃N₄ nanocomposites.³⁹ These nanomaterials were used for the conversion of CO₂ into fuels under the influence of ultraviolet sunlight, optimizing the concentrations of Ag, Ag₃PO₄, and g-C₃N₄. The inclusion of Ag in the photocatalyst significantly improved its light absorption capacity and enhanced the separation of electron-hole pairs through the Z-scheme mechanism, leading to a remarkable improvement in the photocatalytic CO₂ reduction performance. Our optimized Ag₃PO₄/g-C₃N₄ nanocomposite exhibited a CO₂ conversion rate 6.1 and 10.4 times higher than that of g-C₃N₄ and P, respectively. These findings demonstrate a groundbreaking application of the photocatalyst in simultaneously addressing environmental concerns and generating energy. A recent research study

successfully tackled the challenges associated with creating highly efficient g-C₃N₄-based photocatalysts for H₂ production. By utilizing a simple probe sonication-assisted liquid exfoliation method, the researchers prepared g-C₃N₄ nanosheets (g-C₃N₄ NS) and developed a 2D-2D MoS₂/g-C₃N₄ NS photocatalyst for photocatalytic H₂ production, which outperformed the traditional 0D-2D Pt/g-C₃N₄ photocatalyst. The improved performance was attributed to the large surface area and the formation of 2D interfaces between MoS₂ and g-C₃N₄ nanosheets, which facilitated accelerated photoinduced charge transfer. This study introduced a new approach to developing highly efficient g-C₃N₄-based photocatalysts for H₂ production by using 2D nanojunctions.^{14,40}

Another study focused on the development of photocatalysts based on N-vacancy tubular graphitic carbon nitride (NvT/g-C₃N₄). The nanocomposite was fully decorated with dispersed Mo metal, resulting in the formation of the novel composition of Mo/NvT/g-C₃N₄. The authors successfully addressed the challenges associated with achieving a high density of metal center agglomeration in single-atom catalysts. The unique structure of NvT/g-C₃N₄ provided a large surface area that effectively suppressed the agglomeration of Mo particles. Moreover, the presence of nitrogen atom defects facilitated the configuration between the light absorbers and the Mo sites in Mo₋₂C/2N. The photocatalyst made up of Mo/NvT/g-C₃N₄ has demonstrated remarkable photoelectric features and has shown to be highly efficient in degrading tetracycline compounds when exposed to visible light. Mo/NvT/g-C₃N₄ demonstrated remarkable potential as a practical photocatalyst.⁴¹ The application in pollutant degradation demonstrates not only the environmental relevance of g-C₃N₄ but also its adaptability to tackle complex chemical challenges.

In recent research studies, the application of g-C₃N₄ derivatives in photocatalysis technology, particularly in algae remediation, was also investigated.²² Researchers successfully exfoliated g-C₃N₄ using sulfuric acid to obtain a novel nanocomposite called S-g-C₃N₄. This nanocomposite exhibited effective photocatalytic properties for algae inactivation under visible light irradiation. S-g-C₃N₄ showed positive surface charge, and small-sized and ultrathin structure, resulting in enhanced adsorption on algal cells, efficient charge transfers, and separation. The addition of H₂O₂ significantly improved the

inactivation efficiency by reducing the recombination of photo-induced carriers and generating more OH radicals. The findings demonstrated the inactivation of algal cells, reduced photosynthetic activity, membrane damage, cell rupture, and improved removal of organic waste.^{42,43}

In another research study, g-C₃N₄ was prepared as a 2D structure with tunable and movable electronic properties, offering significant chemical stability, visible light sensitivity, and photocatalytic capabilities. However, pure g-C₃N₄ exhibited limited sunlight absorption activity and low surface area, leading to reduced photocatalytic activity due to the rapid recombination of electron-hole pairs.⁴⁴

Polymeric graphitic carbon nitride (p-g-C₃N₄) shares similar structural features with graphene and exhibits high chemical and thermal stability due to polycondensation. Its band positions and band gaps can be modified through copolymerization and doping, enhancing its activity as an effective photocatalyst, particularly in photochemical water splitting via selective photo-oxidation.^{45,46}

Graphitic carbon nitrides (g-C₃N₄) are a unique class of materials that exhibit exceptional properties, thereby holding great potential for a wide range of applications in photocatalysis,

heterogeneous catalysis, and fuel cells. Zheng *et al.* have thoroughly explained these properties and their applications. In recent years, a significant amount of research has gone into the development of various types of nanostructured and nanoporous g-C₃N₄ materials with controllable structures and morphologies. These materials have been synthesized using various methods, and the result has been a wide range of g-C₃N₄ nanomaterials. This article aims to provide a comprehensive overview of these different types of g-C₃N₄ nanomaterials, including their synthesis methods and categorizes their applications as efficient and multifunctional metal-free catalysts. The article also highlights the potential applications of these nanostructured g-C₃N₄ materials in artificial photocatalysis for hydrogen production, oxygen reduction reaction for fuel cells, and metal-free heterogeneous catalysis. Overall, these materials have been found to be highly useful in various environmental protection, energy conversion, and storage applications. The article also includes a visual representation of these applications in Fig. 3 to aid in better understanding.⁴⁶ g-C₃N₄ is at the forefront of material innovation, offering sustainable solutions for various global challenges.⁴⁷

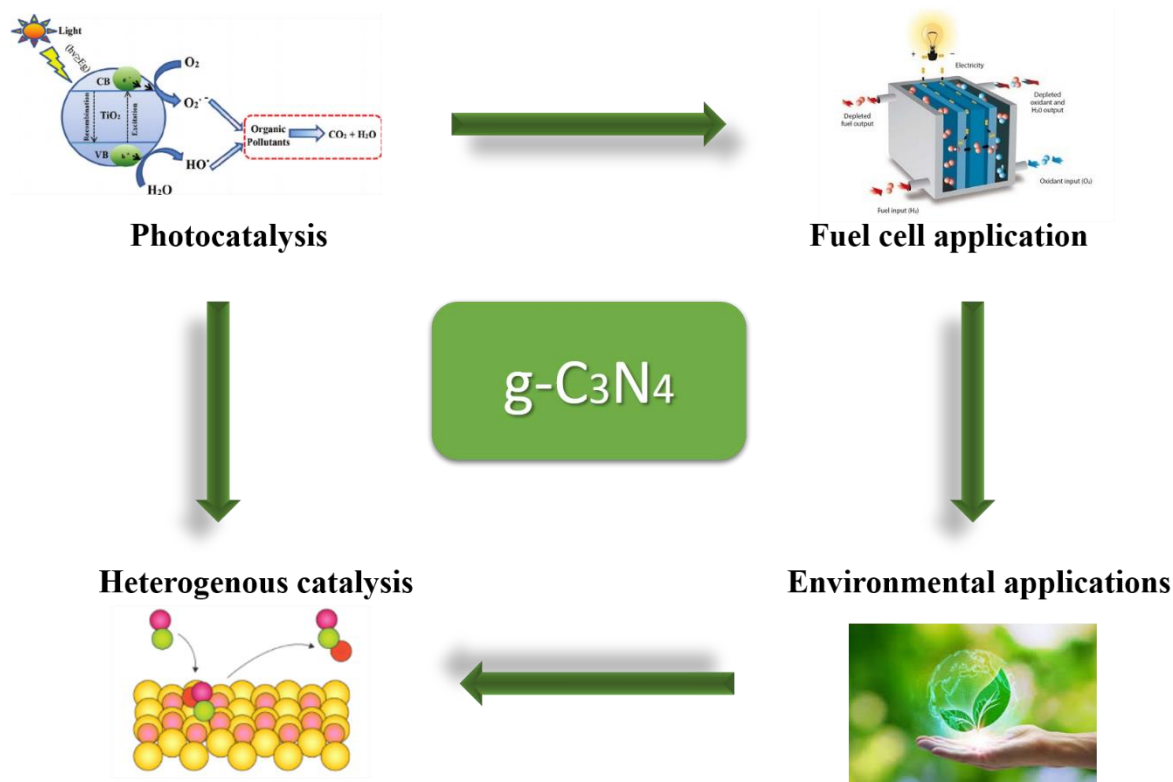


Fig. 3 – g-C₃N₄ incorporated composition represented in the cyclic form of four fundamental applications including the environment, heterogeneous catalysis, photocatalysis, and fuel cells.^{46,48}

ENERGY STORAGE BATTERIES

In terms of energy storage and conversion, electrochemical (redox) reactions play a vital role in converting chemical energy stored in active materials within batteries into electric energy. A cell serves as a fundamental electrochemical unit for the generation or storage of electric energy, while a battery refers to the combination of one or more cells connected in different configurations, such as series or parallel, to achieve the desired output voltage and capacity. $g\text{-C}_3\text{N}_4$ emerged as a promising material for use in lithium-ion batteries due to its exceptional electrical conductivity, stability, improved electrochemical performance, and environmentally friendly composition. Its use aligns perfectly with the increasing demand for sustainable and efficient materials in energy storage technologies, highlighting its eco-friendly advantages.⁴⁷

Due to its unique properties, graphitic carbon nitride has garnered significant attention across various energy fields, primarily in energy storage and conversion. Its multi-layered structure with tunable bandgap, metal-free nature, and enhanced physicochemical stability make it a highly desirable material for energy optimization. The 2D structure of $g\text{-C}_3\text{N}_4$ nanosheets offers short electron/mass transfer paths and abundant reactive sites, which makes them highly suitable for diverse applications. These characteristics present an exciting opportunity to revolutionize energy storage systems, making them faster, more reliable, and environmentally benign.⁴⁹ However, despite its potential, comprehensive studies on the applications of 2D $g\text{-C}_3\text{N}_4$ composites in energy conversion and storage are still limited. A recent review highlighted the versatile applications of $g\text{-C}_3\text{N}_4$ across various synthesis techniques and energy-related fields. Methods like thermal oxidation etching, chemical exfoliation, ultrasonication-assisted liquid phase exfoliation, and chemical vapor deposition enhanced $g\text{-C}_3\text{N}_4$ properties such as surface area, porosity, and electron mobility. These tailored materials excel in energy applications, including photocatalytic and electrocatalytic H_2 evolution (up to $200 \mu\text{mol g}^{-1} \text{h}^{-1}$ and low overpotentials of 50–150 mV, respectively), O_2 evolution/reduction (with current densities of 10–20 mA cm^{-2}), and CO_2 reduction (yielding 10–30 $\mu\text{mol g}^{-1} \text{h}^{-1}$). Additionally, $g\text{-C}_3\text{N}_4$ demonstrated potential in Li-metal and Li-S batteries, metal-air batteries, and

supercapacitors, providing enhanced stability, high energy densities, and long cycle life, making it a promising candidate for advancing energy technologies.^{50,51,52} The breadth of applications reviewed is impressive, reflecting the material's versatility and highlighting its potential to serve as a cornerstone for future advancements in energy technologies.

Another study discussed a heteroatom-refilling strategy employed to enhance the conductivity of nitrogen-deficient $g\text{-C}_3\text{N}_4$ as a high-performance electrode in lithium-ion batteries.²¹ The researchers utilized high-energy hydrogen plasma bombardment to generate $g\text{-C}_3\text{N}_4$ with a high density of nitrogen vacancies, which were subsequently refilled with oxygen upon exposure to air. The conductivity and electrochemical performance of $g\text{-C}_3\text{N}_4$ improved significantly after being refilled with oxygen. It demonstrated an impressive capacity of $647 \text{mAh} \cdot \text{g}^{-1}$ after 400 cycles at $0.1 \text{A} \cdot \text{g}^{-1}$. Furthermore, a cycle of $232.8 \text{mAh} \cdot \text{g}^{-1}$ was maintained over an extended period of 5000 cycles at $1 \text{A} \cdot \text{g}^{-1}$, indicating excellent stability. This innovative approach is a testament to the power of precise material engineering in addressing the limitations of traditional battery electrodes, potentially revolutionizing the field of high-performance energy storage.

The enhanced performance can be attributed to a combination of factors, including reduced band gap, improved lithium absorption energy, modulation of charge density by vacancy engineering, increased specific surface area, and active sites due to plasma bombardment.⁴⁹

These findings suggested significant potential for further development and application of this material in energy storage technology. These findings highlighted the effectiveness of the heteroatom-refilling strategy and plasma-based methods for energy storage and electronic devices.

Another study reported the successful synthesis of a hierarchical $g\text{-C}_3\text{N}_4/\text{WS}_2$ nanocomposite, which served as a smart material for the anode electrode in modern lithium-ion batteries (LIBs).⁵³ Transition metal sulfides (TMSs) were incorporated into the $g\text{-C}_3\text{N}_4/\text{WS}_2$ nanocomposites to address the limitations of TMSs, which include low electronic conductivity and large volume variations. The solvothermal synthesis of $g\text{-C}_3\text{N}_4/\text{WS}_2$ nanocomposites enabled the utilization of $g\text{-C}_3\text{N}_4$ nanosheets, which provided active sites for lithium

storage and act as a buffer to accommodate the volume changes of WS₂ nanocomposites. Furthermore, the ultrathin g-C₃N₄ nanosheets prevented agglomeration of WS₂ and enhanced contact with the electrolyte, facilitating charge transport and ion diffusion. The optimized g-C₃N₄/WS₂ nanoelectrode demonstrated promising performance, with a large discharge capacity of 1136.1 mAh g⁻¹ at 0.1C and excellent

cycling stability of 433.8 mAh g⁻¹ after 1000 cycles. This research confirmed the hierarchical structure and high activity of g-C₃N₄/WS₂ nanocomposites as an anodic nanomaterial for LIBs. The solvothermal synthesis method showcased the effective construction of hierarchical transition metal sulfide-based materials with potential applications in various fields.

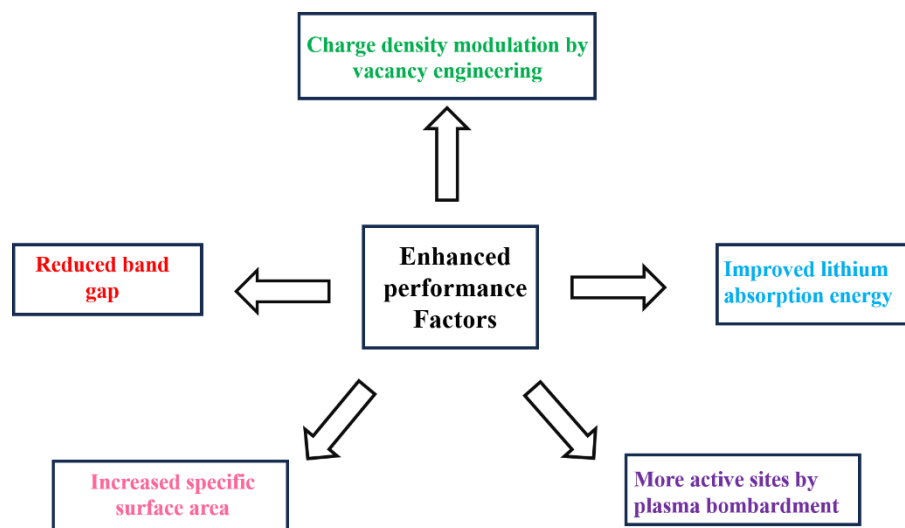


Fig. 4 – Flowchart diagram representing the factors contributing to enhanced performance in energy storage materials.

Renewable energy technologies significantly advanced with the aid of energy storage materials. A recent study has been conducted to develop a covalent organic framework (COF)/graphitic carbon nitride (g-C₃N₄) nanocomposite using a one-pot process.⁵⁴ The researchers synthesized the COF and COF/g-C₃N₄ nanocomposites by condensing melamine and benzene-1,3,5-tricarboxyaldehyde, with or without the presence of g-C₃N₄. The next step involved the carbonization of COF and COF/g-C₃N₄ to obtain N-doped carbon and N-doped carbon/g-C₃N₄, respectively. These materials were then used as electrode materials in supercapacitors and lithium-ion batteries. The results were impressive, with specific capacitance ranging from 211 to 835.2 F·g⁻¹ for COF, COF/g-C₃N₄, N-doped carbon, and N-doped carbon/g-C₃N₄, indicating their potential as promising candidates for energy storage applications. A supercapacitor device with an asymmetric design incorporating N-doped carbon/g-C₃N₄ exhibited a remarkable energy of 45.97 Wh·kg⁻¹ and power of 659.3 W·kg⁻¹. Additionally, the electrode made of N-doped carbon/g-C₃N₄, showed a discharge capacity of 390 mAh·g⁻¹ at 50 mA·g⁻¹ when tested in lithium-ion batteries. The feasibility of lithium-sulfur (Li-S) batteries for commercial use is limited by the

sluggish redox kinetics and the polysulfide shuttle effect. This issue is addressed in this study by developing a nanocomposite consisting of CoS anchored on g-C₃N₄ nanosheets, known as CoS/g-C₃N₄. This nanocomposite is integrated into an ultrathin polypropylene membrane with a small amount of conductive Ketjen black, forming a multifunctional interlayer. The interlayer effectively captures polysulfides via Li-N bonding and Lewis acid-base interactions, while also catalyzing the redox conversion of intermediate polysulfides. Consequently, a Li-S cell incorporating this modified separator and a high-sulfur-content cathode exhibits excellent performance, delivering a capacity of 1290 mAh g⁻¹ and exhibiting a low fading rate of 0.03% per cycle after 500 cycles at 1.0C. Moreover, a high sulfur mass loading of 4.0 mg·cm⁻² electrode, combined with the multifunctional separator, maintains a stable specific capacity of 600 mAh g⁻¹ after 250 cycles under 0.1C. This research provided valuable insights into the design of thin and lightweight interlayers for enhancing the utilization of sulfur species while preserving energy density and Li-ion transportation in Li-S batteries.⁵⁵

Tang *et al.*⁵⁶ have synthesized 3D composite electrodes supported by g-C₃N₄ nanowire (g-

C₃N₄ NW) work as scaffolds, and poly (3,4-ethylene dioxothiophene) and poly (4-styrene sulfonate) as conducting polymer. An electrode based on graphitic carbon nitride demonstrates a specific capacitance of 202 F g⁻¹ and retains 83.5% of its initial capacitance even after undergoing 5000

cycles. Additionally, this electrode displayed impressive performance in terms of capacitance, cycling stability, and flexibility.⁵⁶ Carbon-based nanomaterials have been reported to show unique applications in electronic pieces of equipment, like supercapacitors⁵⁶ are mentioned in Fig. 4.

Table 1

Summary of Recent Advancements in Graphitic Carbon Nitride (g-C₃N₄)-Based Nanocomposites for Energy Storage Applications

Materials/Methods	Applications	Key results	Study/Reference
g-C ₃ N ₄ /WS ₂ nanocomposites synthesized via solvothermal method	Lithium-ion batteries (LIBs)	Large discharge capacity of 1136.1 mAh g ⁻¹ at 0.1C; cycling stability of 433.8 mAh g ⁻¹ after 1000 cycles.	53
COF/g-C ₃ N ₄ nanocomposites via one-pot synthesis; carbonized into N-doped carbon materials	Supercapacitors and LIBs	Specific capacitance: 211–835.2 F·g ⁻¹ ; supercapacitor energy: 45.97 Wh·kg ⁻¹ ; LIB discharge capacity: 390 mAh·g ⁻¹ at 50 mA·g ⁻¹ .	54
CoS/g-C ₃ N ₄ nanocomposite integrated into polypropylene membrane with Ketjen black	Lithium-sulfur (Li-S) batteries	Li-S cell capacity: 1290 mAh g ⁻¹ ; fading rate: 0.03% per cycle over 500 cycles; high sulfur mass loading (4.0 mg·cm ⁻²) achieves 600 mAh g ⁻¹ after 250 cycles at 0.1C.	55
3D composite electrodes with g-C ₃ N ₄ nanowires as scaffolds; poly(3,4-ethylene dioxothiophene) and PSS	Supercapacitors	Specific capacitance: 202 F g ⁻¹ ; retains 83.5% capacitance after 5000 cycles; high cycling stability and flexibility.	56

Carbon-based nanomaterials have been reported to show unique applications in electronic

devices like supercapacitors⁵⁶ are mentioned in Fig. 5.

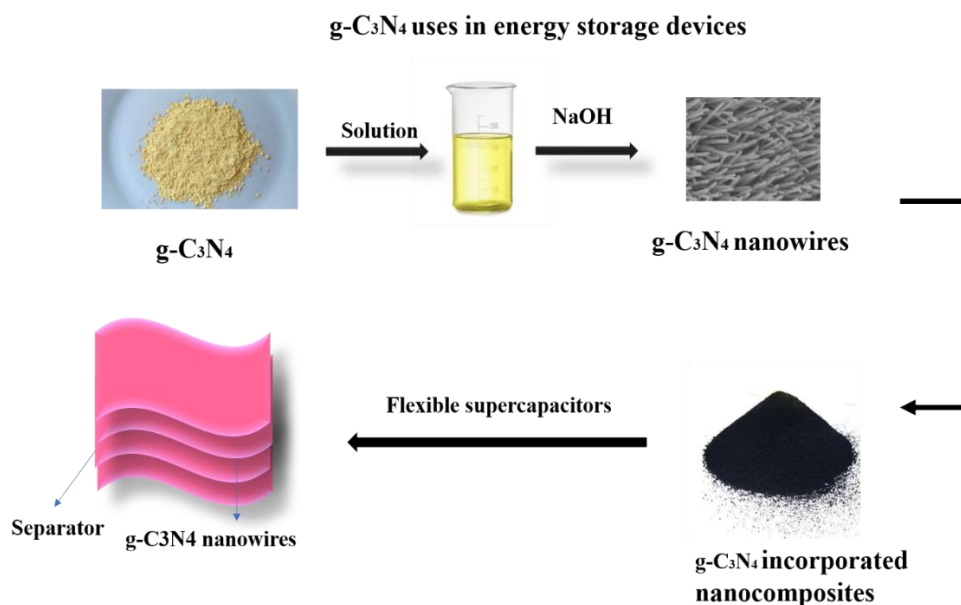


Fig. 5 – Graphitic carbon nitride nanowires utilization in two basic electronics applications such as flexible supercapacitors and three electrode circuits.⁵⁶

SENSORS

Graphitic carbon nitrides (g-C₃N₄) emerged as a promising 2D polymeric nanomaterial composed predominantly of nitrogen and carbon atoms. It

attracted considerable attention due to its unique optical and electrical characteristics, making them suitable for various applications in sensing, imaging, and treatment. In this context, the luminous properties of g-C₃N₄ nanomaterials are of particular

interest and have been thoroughly examined and evaluated. These properties primarily include photoluminescence and electrochemiluminescence, as well as catalytic and photoelectronic properties, which are closely associated with sensing and therapeutic applications.⁵⁷ These multifunctional luminous properties offer exciting possibilities for advanced diagnostic tools and therapeutic systems, paving the way for more efficient and integrated biomedical devices.

Graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) has been the focus of recent research due to its potential as an environmentally friendly, cost-effective, and metal-free photocatalyst. This 2D conjugated polymer has unique electronic properties, is non-toxic, and can be synthesized at a low cost. $g\text{-C}_3\text{N}_4$ possesses remarkable electronic band structures, which give it a unique set of properties that make it highly desirable for a wide range of technological applications. Its electron-rich characteristics, along with its basic surface functionalities, make it particularly attractive for use in catalysis, sensing, imaging, and white-light-emitting diodes.⁵⁸

The combination of low cost, non-toxicity, and superior electronic properties makes $g\text{-C}_3\text{N}_4$ a game-changer, offering a sustainable and scalable solution to various industrial challenges while maintaining environmental integrity. Additionally,

its high physicochemical stability ensures that it can perform reliably under a variety of environmental conditions, making it an ideal material for use in demanding industrial settings.

Various research studies⁵⁹ and industries have shown significant interest in $g\text{-C}_3\text{N}_4$. One study by Idris et al. highlighted its high quantum yield, catalytic ability, metal-free nature, and low bandgap energy. $g\text{-C}_3\text{N}_4$ can act as a nano mediator and immobilization layer in detecting different biomolecules, making it useful in constructing electrochemical sensors and biosensors. Several techniques have been extensively applied to detect biological molecules and heavy metals with high sensitivity and selectivity using graphitic carbon nitride ($g\text{-C}_3\text{N}_4$). Recent developments have incorporated $g\text{-C}_3\text{N}_4$ with copper metal, leading to the creation of new formulations. These formulations are working as electrochemical sensors and biosensors. This innovative incorporation of copper further enhances the material's capabilities, illustrating how strategic modifications can expand its application horizon, particularly in the development of next-generation electrochemical devices.

A few examples of Cu-based nanocomposites used in biosensors, such as dopamine and glucose, are mentioned⁵⁹ as displayed in Fig. 5.

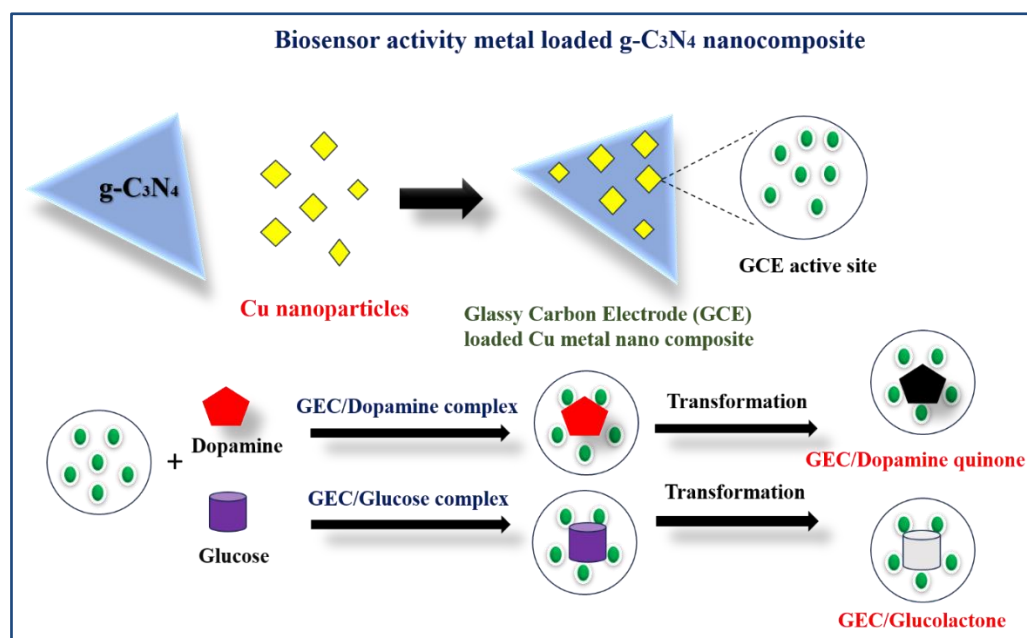


Fig. 5 – Graphitic carbon nitride incorporated with Cu metal to achieve $g\text{-C}_3\text{N}_4/\text{Cu}$ (commonly known as glassy carbon electrode (GCE)). This composition was used to visualize dopamine and glucose into dopamine quinone and glucolactone respectively.⁵⁹

Malik *et al.* conducted a study that introduced a highly responsive and sensitive sensor for relative humidity (% RH).⁶⁰ The sensor employed a highly

advanced material called cubic mesoporous graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) that was loaded with In-SnO_2 . This material was synthesized via a

nano-casting process that utilized mesoporous silica as a template. The ordered mesopores of the cubic structure of this material significantly improved the sensor's ability to adsorb, transmit charges, and desorb water molecules on its surface. As a result, the sensor could detect and respond to changes in its surrounding environment more effectively. The optimized nanohybrid exhibited outstanding performance, displaying a significant response (5 orders change in impedance) within the 11–98% RH range, along with excellent stability, minimal hysteresis, and superior real-time % RH detection capabilities. The remarkable responsiveness and stability of this sensor represent a breakthrough in humidity monitoring, showing great potential for applications in fields like healthcare and environmental monitoring. Recent studies have shown that the 3D mesostructured In-SnO₂/meso-CN nanohybrid exhibits significantly faster response and recovery times (3.5 s and 1.5 s, respectively) at room temperature compared to traditional metal oxide-based sensors. These findings have promising implications for breath monitoring and highlight the potential of mesoporous 2D layered materials in the future development of highly sensitive % RH sensors. The rapid response and recovery times could revolutionize real-time monitoring technologies, particularly in medical diagnostics, such as breath analysis, where speed and precision are crucial. This innovative approach to detecting nitro-containing aromatics provides a powerful tool for monitoring environmental pollution and detecting chemical hazards, making it an invaluable resource in ensuring public safety.⁶⁰

Additionally, another study has successfully synthesized a zinc oxide-graphitic carbon nitride (ZnO/g-C₃N₄) nanohybrid material by loading zinc oxide with graphitic carbon nitride.⁶¹ The synthesis was carried out using a one-pot thermal decomposition assay, employing a single-source molecular precursor for ZnO synthesis and urea for the preparation of g-C₃N₄. The resulting ZnO/g-C₃N₄ nanocomposite was modified with a glassy carbon electrode (GCE) to obtain a ZnO/g-C₃N₄/GCE surface. This nanohybrid material was used to detect aromatic compounds containing nitro groups (-NO₂). The developed ZnO/g-C₃N₄/GCE sensor exhibited remarkable sensitivity with low detection limits for various compounds. Additionally, the ZnO/g-C₃N₄ materials demonstrated superior photocatalytic degradation of organic pollutants, achieving high percentages of

degradation for several substances. The excellent performance of the ZnO/g-C₃N₄/GCE nanohybrid in sensing -NO₂-containing aromatics and degrading organic pollutants can be attributed to its higher surface area and the formation of a heterojunction at the interface of ZnO and g-C₃N₄, facilitating electron transfer processes.

Huang *et al.* (2014) successfully developed g-C₃N₄ nanofilms (g-C₃N₄NF) and demonstrated them as solid fluorescence sensors. These g-C₃N₄NF nanocomposites exhibited exceptional properties, including convenience, sensitivity, selectivity, speed, and reusability, for detecting Cu²⁺ and Ag⁺ in water and serum samples. It highlighted the potential application of these sensors in disease diagnosis, as they can differentiate between Cu²⁺ and Ag⁺ based on the disparities in their adsorption and desorption kinetics methodologies.^{62,63} The differentiation of metal ions through innovative kinetics underscores the ingenuity of this technology, offering promise for selective and efficient diagnostic solutions.

This study addressed the global concern of heavy metal ion (HMI) pollution by proposing an easy and cost-effective method for monitoring HMIs in environmental water. Using an in-situ electrochemical polymerization deposition technique, the scientists created a modified screen-printed carbon electrode (SPE) that utilized a novel nanonetwork consisting of poly (melamine) and graphitic-carbon nitride (PM/g-C₃N₄). The g-C₃N₄ nanomaterial was synthesized from melamine via pyrolysis and subsequently polymerized and deposited onto the SPE using cyclic voltammetry. The resulting PM/g-C₃N₄/ASPE electrode was characterized using XRD, XPS, and SEM. This electrode was then utilized as an environmental sensor for the simultaneous and selective electrochemical detection of toxic HMIs, specifically Pb²⁺ and Cd²⁺ ions, employing differential pulse voltammetry.

The developed sensor exhibited outstanding sensitivity and selectivity, with detection limits of 0.008 μM for Pb²⁺ and 0.02 μM for Cd²⁺. It also demonstrated stability, repeatability, anti-interference properties, and applicability for analyzing real water samples. Based on the findings, the study concluded that the PM/g-C₃N₄/ASPE sensor represented a practical, low-cost, and efficient platform for rapid and simultaneous monitoring of HMIs in the environment⁶⁴. This innovation offers a scalable and sustainable solution to environmental monitoring, emphasizing its real-

world applicability and impact in tackling heavy metal contamination.

BIOMEDICALS

The biomedical field has taken a keen interest in $g\text{-C}_3\text{N}_4$ due to its remarkable electronic and optical properties, attracting significant attention. According to a recent review paper, $g\text{-C}_3\text{N}_4$'s biomedical applications, including therapeutic applications, diagnostic imaging, biosensors, and antibacterial applications, have seen recent advances.³ The authors of the paper also provided a comprehensive overview of the systematic preparations of $g\text{-C}_3\text{N}_4$ and included a detailed discussion of the biosafety and toxicity evaluations of $g\text{-C}_3\text{N}_4$ -based materials. The collective findings strongly support the belief that emerging $g\text{-C}_3\text{N}_4$ -based bionanomaterials hold immense potential for realizing practical biomedical applications. This comprehensive review highlights the versatility and future promise of $g\text{-C}_3\text{N}_4$ in transforming the biomedical landscape, particularly due to its systematic development and evaluation in terms of safety and functionality.

Lin *et al.*⁶⁵ developed two-dimensional graphitic-phase carbon nitride ($g\text{-C}_3\text{N}_4$) nanosheets, highlighting their potential in bioimaging, photodynamic therapy (PDT), and drug delivery due to their unique composition and properties. Composed of layered sp^2 -hybridized carbon and nitrogen in a graphitic structure, these nanosheets

exhibit high photoluminescence, low toxicity, and excellent biocompatibility. They demonstrated strong fluorescence for stable and bright bioimaging, efficient ROS generation under visible light for effective tumor cell apoptosis in PDT, and pH-responsive drug release in acidic tumor environments. With high drug-loading capacities (~ 20 wt%) and controlled release profiles, these nanosheets offer significant potential for multifunctional biomedical applications. Under low-intensity light irradiation (20 mW cm^{-2}), $g\text{-C}_3\text{N}_4$ nanosheets can generate reactive oxygen species (ROS) and eliminate cancer cells as photosensitizers. Moreover, $g\text{-C}_3\text{N}_4$ nanosheets have a high drug-loading capacity due to their high surface-to-volume ratio and thus can act as nanocarriers. Importantly, $g\text{-C}_3\text{N}_4$ nanosheets loaded with the anticancer drug doxorubicin (DOX) exhibited a property of releasing DOX in response to pH, which facilitates drug delivery to cancer cells for chemotherapy. These findings indicated that $g\text{-C}_3\text{N}_4$ nanosheets have potential as biocompatible and low-toxic photosensitizers and pH-responsive drug nanocarriers, making them a promising option for various biomedical applications. The multifunctionality of $g\text{-C}_3\text{N}_4$ nanosheets in diagnostics and therapy positions them as a cornerstone for future advancements in nanomedicine, driving innovation in cancer treatment and beyond. Combinations of different therapies along with reference drugs give better anticancer treatment^{65,66,67} as shown in Fig. 6.

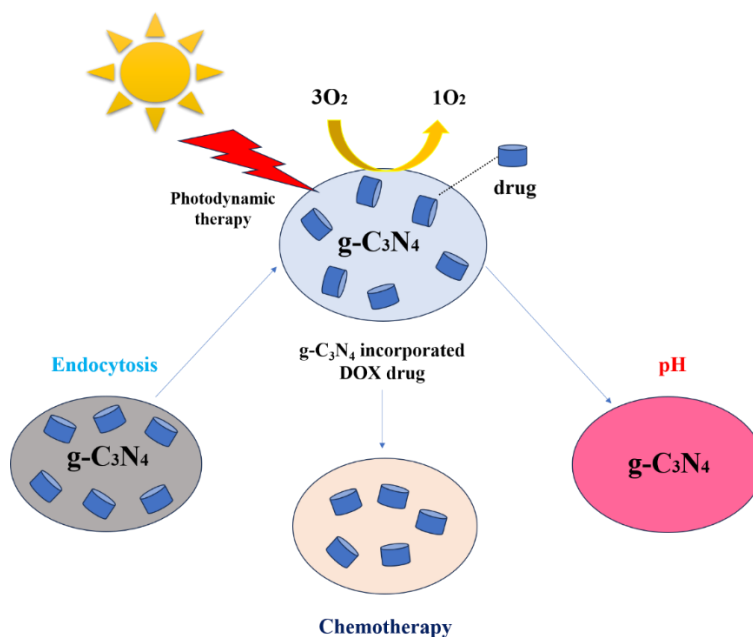


Fig. 6 – Emergence of phototherapy and chemotherapy effect of $g\text{-C}_3\text{N}_4$ incorporated DOX drug. This composition works under lower pH and gives ROS mechanism without damage to the $g\text{-C}_3\text{N}_4$ matrix.⁶⁵

ANTICANCER ACTIVITY

In the modern era, cancer is a global challenge, driving the search for new and effective drugs. Nanodrugs emerged as a promising approach for targeting cancer cells while minimizing harm to healthy cells. However, many anticancer drugs developed in the past few decades exhibited significant levels of toxicity, impacting not only cancerous cells but also affecting healthy areas of the human body. In response, some authors explored the potential of using terrestrial plants and marine environments to develop novel anticancer drugs.⁶⁸ Building on this quest for safer and more effective treatments, researchers have also turned to nanotechnology as a means of enhancing drug delivery and reducing systemic toxicity. In one such study, the cisplatin (Cis-Pt) drug was loaded onto g-C₃N₄ to evaluate the properties and anticancer activity of Cis-Pt/g-C₃N₄ nanocomposites. The nanocomposites were evaluated at two different states (+1/−1) of g-C₃N₄ to determine the optimal drug performance.¹² The biological activity of the nanocomposites was confirmed through the adsorption energy of H and N atoms at −1.25 eV. Weak non-covalent interactions were observed between g-C₃N₄ and cisplatin, playing a crucial role in drug loading and release at the target site. Both the +1/−1 charge states of g-C₃N₄ exhibited negligible effects on structural distortion and formed stable complexes with the applied drug. Overall, the research suggested that g-C₃N₄ can serve as an efficient drug delivery platform for the treatment of various forms of cancer cells. This study is particularly exciting because it showcases g-C₃N₄'s ability to maintain structural stability while facilitating targeted drug delivery – a critical factor in reducing side effects and maximizing therapeutic efficacy.

Density Function Theory (DFT) studies were conducted to evaluate the chemotherapeutic effects of g-C₃N₄ as a drug carrier, specifically when combined with carboplatin (C-Pt) to create a novel formulation called C-Pt/g-C₃N₄. The anti-cancer abilities of the nanof ormulation were assessed using optimized conditions for electronic configuration in the excited state of g-C₃N₄, bare carboplatin, and g-C₃N₄-carboplatin complexes targeting specific sites. The complex exhibited an absorption energy of −1.39 eV in the gas phase and −0.52 eV in the water phase. Non-covalent interactions between C-Pt/g-C₃N₄ were also observed, facilitating drug release. Both states of g-C₃N₄ (g-C₃N₄+1/−1) exhibited

minimal structural distortion, resulting in more stable carboplatin-based complexes. The results confirmed that g-C₃N₄ showed chemotherapeutic potential as a drug carrier in cancer treatment.^{13,69,70} The findings here further emphasize the versatility of g-C₃N₄ in cancer treatment, as it demonstrates exceptional compatibility and stability, which are key in ensuring the safe delivery of chemotherapeutics.

g-C₃N₄, with its strong chemical, thermal, and electrical stability, has emerged as a promising material for biomedical applications, particularly in cancer therapy. Composed of a graphitic structure with sp²-hybridized carbon and nitrogen atoms arranged in tri-s-triazine units, g-C₃N₄ exhibits a tunable bandgap (~2.7 eV), high surface area, and the ability to form functional composites. These properties enable it to act as a pH-responsive nanocarrier for controlled drug release in acidic tumor environments. Its composites further enhance drug delivery performance, offering high drug-loading capacities (up to 20–30 wt%) and selective release profiles, reducing systemic toxicity while improving therapeutic outcomes. These characteristics make g-C₃N₄ and its derivatives highly effective in targeted cancer therapy.⁷¹ This aspect of g-C₃N₄ is particularly compelling, as its stability across different conditions suggests potential use in a wide range of biomedical scenarios, especially for diseases requiring long-term treatment solutions.

In another study, PEGylated graphitic carbon nitride quantum dots (g-C₃N₄QD/PEG) were obtained through a high thermal treatment.⁷² g-C₃N₄QDs were added in situ and embedded in the PEG matrix. The inclusion of PEG enhanced the luminescence, stability, and biocompatibility of g-C₃N₄QD/PEG nanocomposites. The prepared nanocomposites were loaded with the reference drug doxorubicin (DOX), which exhibited pH sensitivity for drug release within the cellular environment. The novel g-C₃N₄QD/PEG/DOX nanocomposite demonstrated controlled drug release activity and successfully displayed anticancer effects. This study is particularly noteworthy because the incorporation of PEG not only enhanced the stability and biocompatibility of g-C₃N₄ but also facilitated pH-sensitive drug release, offering a sophisticated approach for targeting cancer cells while sparing healthy tissues. The results indicated that g-C₃N₄QDs/PEG/DOX exhibited improved performance in anticancer activity and cell imaging capabilities⁷² are shown in Fig. 7.

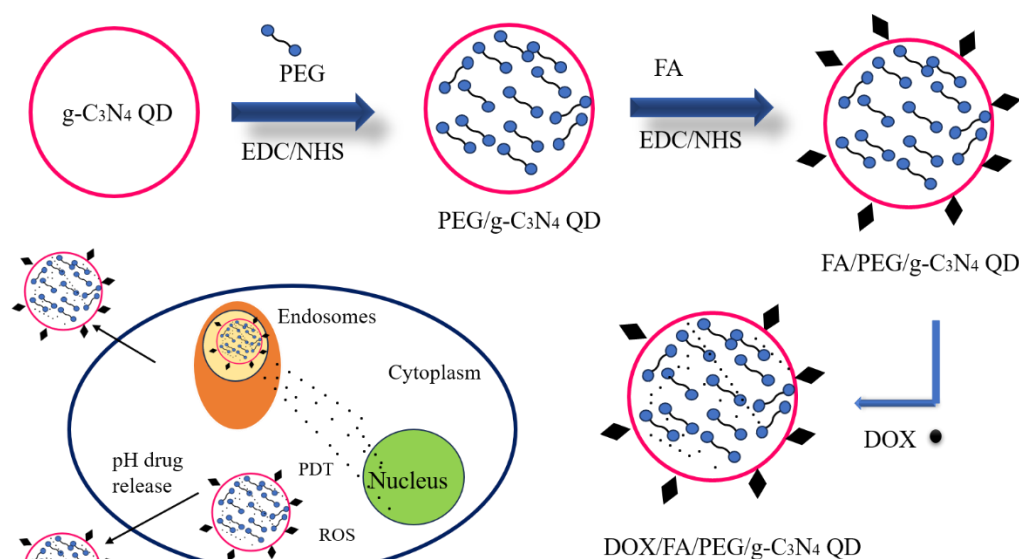


Fig. 7 – Graphitic carbon nitride quantum dots ($g\text{-C}_3\text{N}_4$ QD) were successfully incorporated with PEG, FA, and DOX to form novel DOX/FA/PEG/ $g\text{-C}_3\text{N}_4$ QD. This unique formulation was evaluated against anticancer activity in the presence of phototherapy and chemotherapy.⁷²

In another study, the potential of graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) as a drug carrier was investigated, in combination with the anticancer drug lonidamine (LND).¹⁰ Extensive investigations were conducted to evaluate the efficacy of the $g\text{-C}_3\text{N}_4$ matrix, including the calculation of geometric, electronic, and excited-state properties of bare $g\text{-C}_3\text{N}_4$, LND drug, and the $g\text{-C}_3\text{N}_4$ /LND complex. The adsorption energy of the $g\text{-C}_3\text{N}_4$ -loaded drug complex was approximately -0.40 eV, and an increase in the dipole moment of the complex contributed to its solubility. Complex formation enhanced the hydrophilicity characteristics in biological systems, facilitating easy drug transfer through non-covalent interactions. These weak interactions were advantageous for efficient drug loading and off-loading from $g\text{-C}_3\text{N}_4$ at different target sites. Furthermore, $g\text{-C}_3\text{N}_4$ in both ionic forms ($-1/ +1$) formed stable complexes with LND, exhibiting negligible changes in their structures. Overall, the $g\text{-C}_3\text{N}_4$ /LND system showed significant potential as an anticancer drug release system, particularly for cancer treatment. This study underscores how $g\text{-C}_3\text{N}_4$ can synergize with lonidamine to achieve controlled and efficient drug delivery, particularly by leveraging weak non-covalent interactions. This approach not only enhances solubility but also paves the way for site-specific cancer treatment, minimizing side effects.

Graphitic carbon nitride was recognized as an efficient nano-drug carrier in various drug delivery systems. In a study, $g\text{-C}_3\text{N}_4$ was loaded with the

anticancer drug flutamide (FTD) to create $g\text{-C}_3\text{N}_4$ /FTD nanocomposites and evaluate their effectiveness as drug carriers.⁷³ Different states of $g\text{-C}_3\text{N}_4$, including ground and excited states, exhibited strong noncovalent interactions. The N atoms of $g\text{-C}_3\text{N}_4$ formed weak van der Waals interactions with the O and F atoms of flutamide, facilitating drug loading and offloading within the $g\text{-C}_3\text{N}_4$ /FTD nanocomposite at the targeted site. Overall, $g\text{-C}_3\text{N}_4$ /FTD demonstrated promising results, showcasing high drug loading capacity, low cytotoxicity, and improved anticancer activity. The versatility demonstrated by the $g\text{-C}_3\text{N}_4$ /FTD system is particularly impressive, as it highlights how $g\text{-C}_3\text{N}_4$ can adapt to different molecular interactions to effectively carry and release drugs. This adaptability, combined with its low cytotoxicity, makes it a game-changer in cancer nanomedicine.

In another research paper, the drug delivery efficiency of $g\text{-C}_3\text{N}_4$ as a nanocarrier for the anticancer drug melphalan (MPN) was investigated.¹¹ The study aimed to develop $g\text{-C}_3\text{N}_4$ /MPN nanocomposites and evaluate their drug delivery capabilities for anticancer treatment. The electronic properties of the bare MPN drug, pristine $g\text{-C}_3\text{N}_4$, and $g\text{-C}_3\text{N}_4$ -based complexes were analyzed in both the ground and excited states. The calculated adsorption energy for the novel complex in the water phase was approximately -1.51 eV. Non-covalent interactions were identified between $g\text{-C}_3\text{N}_4$ and the melphalan drug, enabling easy off-loading of melphalan from the $g\text{-C}_3\text{N}_4$ matrix at the

targeted site. This work is fascinating as it demonstrates g-C₃N₄'s capacity to form potent, yet reversible, complexes with melphalan, ensuring precise and efficient drug release. This approach addresses a critical need in chemotherapy by potentially reducing the systemic toxicity of traditional treatments.

ANTIMICROBIAL ACTIVITY

The term "antimicrobial activity" includes the ability of agents to inhibit bacterial growth, impede the development of microbial colonies, and potentially eliminate microorganisms. Thurston et al. reported photoactive nanostructure films derived from metal-free samples, specifically semiconductor graphitic carbon nitride, prepared and characterized for their nanoparticles and antimicrobial potential.⁷⁴ Physical characterization of the nanocomposites revealed discrete dimensions ranging from 200 nm to 700 nm. The photochemical

reactivity of g-C₃N₄ loaded with coumarin-3-carboxylic acid indicated that these nanomaterials generated reactive oxygen species under visible light. Upon irradiation with 0.31 J of visible light, the new materials significantly reduced the cell viability of both Gram-negative *E. coli* and Gram-positive *S. aureus*. Complete inactivation of both strains was achieved with a 0.62 J dose of visible radiation without toxicity. The results of this study strongly suggested that these materials provide novel approaches for controlling pathogens on environmental surfaces, thereby reducing the incidence of hospital-acquired microbial infections. This innovative use of g-C₃N₄ to achieve pathogen inactivation under visible light demonstrates its immense potential in creating safer and non-toxic antimicrobial coatings for surfaces, particularly in high-risk environments like hospitals.

Different form of graphitic carbon nitride-based nanomaterials have given different biological applications, such graphitic carbon nitride in nanoparticle form gives biological activities.⁴⁴

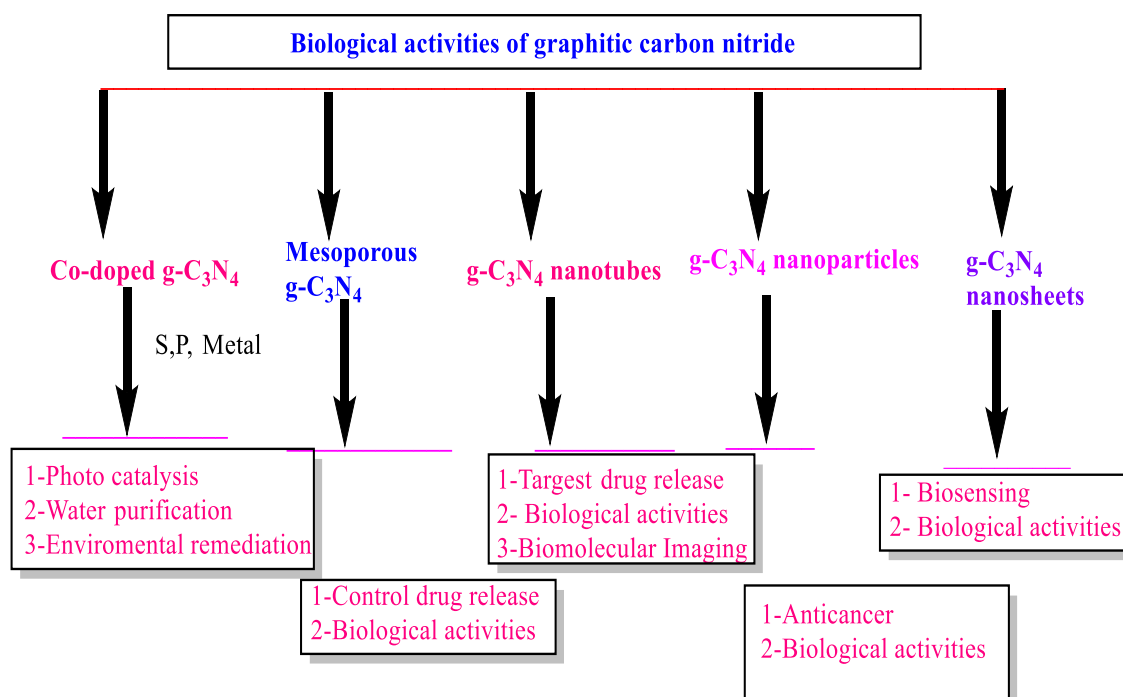


Fig. 8 – All possible forms of g-C₃N₄ are unique for biological activities. In this picture, classified and visualize different performances in the biological activities of g-C₃N₄-based nanocomposites.^{6,7,19,22,24,26,29,45,55,57,58,60,64,65,68,72,75–78}

Thurston *et al.* demonstrated the creation of photoactive biocidal nanofilms using g-C₃N₄.⁷⁹ When exposed to visible radiation, co-deposited films of g-C₃N₄ and *E. coli*, as well as methicillin-sensitive strains of *S. aureus*, exhibited significantly improved bactericidal behavior. A 100 mJ dose of

visible radiation resulted in the complete eradication of microbial samples, while non-irradiated samples did not display any antimicrobial activity. The effectiveness of g-C₃N₄-mediated killing of *Bacillus anthracis* endospores was examined regarding the impact of visible radiation.

Results showed that endospores treated with a 200 mg dose of visible radiation exhibited greater resistance to g-C₃N₄-mediated killing, with only a 25% reduction in spore viability observed. This resistance was attributed to improvements in both the surface area and reduction potential of the material's conduction band edge, as confirmed through its characterization. The study sheds light on the factors influencing the efficacy of g-C₃N₄-based materials in disinfecting endospores, highlighting the need for further research on this subject. This finding underscores the importance of fine-tuning g-C₃N₄'s properties to address the challenges posed by resistant microorganisms, a key step in advancing antimicrobial nanotechnology.

In a separate study, a polyvinylidene fluoride membrane was modified with mesoporous graphitic carbon nitride by immersion-precipitation phase transformation.⁸⁰ The geometry, structure, and morphology of the different hybrid membranes were analyzed using various techniques. An 80-membrane composition demonstrated improved hydrophilicity and antifouling properties, with an increase in the amount of graphitic carbon nitride leading to a decrease in contact angle from 68.33° to 57.12° in the membrane and a 28% improvement in flux recovery ratio. Additionally, the nanomembranes exhibited photocatalytic, self-cleaning, and antimicrobial properties. The 80-hybrid-based nanomembranes were utilized to degrade cefotaxime under sunlight irradiation and achieved 3 logs of *E. coli* inactivation

under visible light for 4 h, with photo-generated reactive oxidative species playing a significant role in both the degradation of organics and bacterial inactivation. The prepared 80-hybrid-based membrane, when exposed to sunlight irradiation, exhibited excellent properties for real wastewater treatment applications.

Orooji *et al.* (2020)⁸¹ have synthesized recombinant nanocomposites of silver iodide (AgI) and graphitic carbon nitride by using sonication-assisted and hydrothermal routes to deposit nanoprecipitates at ambient temperature. By varying the mass ratios and preparation assays, authors were able to modify the structure, shape, purity, and scale of the nanocomposite specimens. The bandgap of pure g-C₃N₄ was measured to be approximately 2.82 eV. However, when incorporating AgI into the nanocomposites, the bandgap was reduced to 2.70 eV. This reduction in the bandgap rendered the nanocomposites suitable for photocatalytic applications, specifically for the degradation of methyl orange and rhodamine B, utilizing visible radiation due to their appropriate bandgap. The AgI/C₃N₄ composite photocatalyst exhibited a significantly enhanced photocatalytic effect compared to pure AgI and g-C₃N₄. This enhancement was attributed to the synergistic interactions between C₃N₄ and AgI, including their inter-attraction within the composites. Additionally, the nanocomposites demonstrated a strong potential for antibacterial action⁸¹ as shown in Fig. 9.

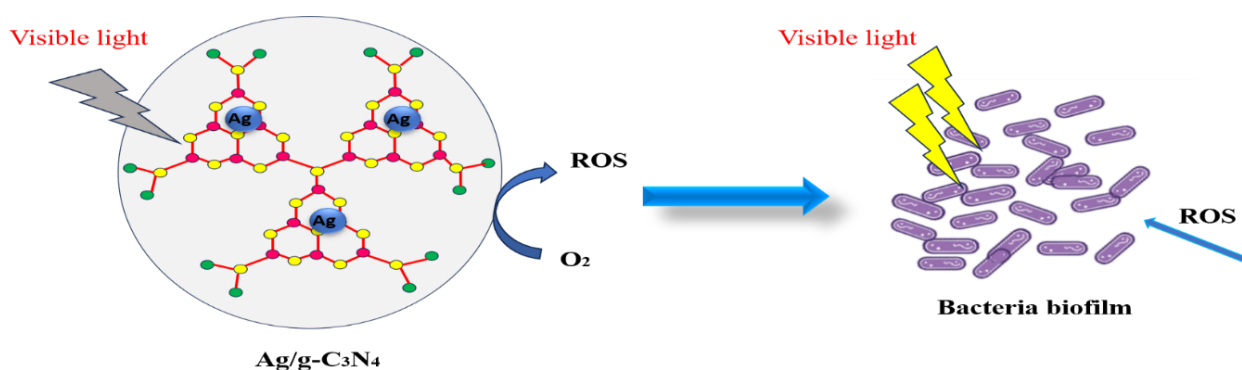


Fig. 9 – Ag particles-loaded g-C₃N₄ to achieve unique Ag/g-C₃N₄ manofilms. This film was tested for anticancer activity. In ROS (reactive oxygen species), a mechanism was reported in biological activity.⁸¹

In recent work, a cost-effective and metal-free electrode modifier was developed to enhance the performance of electrochemical sensors.⁸² The strategy employed heteroatom doping to modify the electronic configuration and support structure. Specifically, oxygen-doped graphitic carbon nitride was synthesized through a single-step thermal polymerization process using urea and oxalic acid.

The characterization results indicated lower impedance, reduced current behavior, and improved surface area. The electrode modifier that was created has a sensitivity to a high current density of 7.784 $\mu\text{A } \mu\text{M}^{-1} \text{cm}^{-2}$. It also has a low detection limit of 0.005 μM and a linear range between 0.01 and 2060 μM . Moreover, the sensor cell viability was evaluated using different samples,

demonstrating desirable antimicrobial results. This innovative electrode design not only highlights the versatility of g-C₃N₄ in the field of sensing but also suggests its dual role as an antimicrobial agent, bridging the gap between environmental monitoring and microbial control.

Concerning health risks posed by waterborne pathogens, sustainable and photocatalytic nanocomposites were synthesized for antimicrobial applications under visible-light conditions.⁸³ The g-C₃N₄/EP-520 composite, comprising graphitic carbon nitride and low-density porous expanded perlite, is highly effective in terms of disinfection. The composite exhibits a specific surface area of 45.3 m²/g and has undergone testing to assess its ability to inactivate *E. coli* under visible-light irradiation at various time intervals. The results indicated that increased levels of dissolved oxygen, proton concentration, salinity, and hardness enhanced the water quality parameters. These findings are crucial for the development of effective water treatment methods to improve water quality and ensure safe drinking water for everyone. Notably, the g-C₃N₄/EP-520 composite showed negligible activity loss during prolonged light irradiation, indicating its robustness and potential for pathogen removal. The antimicrobial mechanisms were evaluated using the radical scavenger method, which confirmed the destruction of bacterial and viral particles.

Other authors reported that membrane fouling significantly hindered membrane performance, and functionalized membranes demonstrated excellent photocatalytic and antimicrobial activity.⁸⁴ The self-cleaning nature of these membranes is a significant advancement, offering a practical solution to the pervasive problem of membrane fouling. Composite membranes were obtained by filtering g-C₃N₄ onto a porous matrix of polyacrylonitriles. These functionalized g-C₃N₄ nanosheet composite membranes exhibited a water permeability of 11.70 L m⁻² h⁻¹ bar⁻¹ and demonstrated strong antibacterial properties. The membranes were capable of restoring their initial color and permeability even after three cycles of rejecting dyes and post-treatment under different visible light irradiation conditions. This nano-membrane holds potential feasibility in wastewater treatment and provides an alternative route for fabricating self-cleaning nano-membranes.

In recent research, a novel combination of Pd nanoparticles embedded in banana leaf extract modified with graphitic carbon nitride was

developed through a suitable and facile 3-step reaction.⁸⁵ This work exemplifies the power of green synthesis, where sustainable methods not only reduce environmental impact but also produce multifunctional nanomaterials with impressive antibacterial and catalytic properties. The active phytochemicals present in the banana extract acted as reducing, capping, and stabilizing agents, leading to the *in-situ* reduction of Pd from (II) to (0) oxidation state. Importantly, these synthesis methods were entirely free from toxic reagents, catalysts, harsh conditions, and additional reducing agents. The nanocatalysts exhibited excellent catalytic performance in Suzuki-Miyaura coupling and aryl halide cyanation reactions under mild conditions. The advantages of Pd-based nanocomposites include short reaction times, high yields, a heterogeneous nature, easy work-up, recyclability, and a straightforward procedure, all while maintaining their catalytic activity. Furthermore, the PdNPs/g-C₃N₄/banana leaf extract nanocatalyst displayed extraordinary antibacterial properties against both gram-negative *E. coli* and gram-positive *B. subtilis* bacteria.

TISSUE ENGINEERING

Polycaprolactone (PCL) biopolymers find extensive use in biomedical applications⁸⁶. However, challenges such as hydrophilicity, degradation rate, and cellular response are reported when PCL is used for tissue engineering. To overcome these issues, a study focused on incorporating g-C₃N₄ nanosheets (g-C₃N₄ NS) into PCL nanofibrous scaffolds (PCL NF) using electrospinning.⁸⁷ The effects of g-C₃N₄ NS on the composite scaffolds were characterized through various techniques, including the evaluation of mechanical properties, biocompatibility, biodegradability, and contact angle. The results strongly demonstrated that the inclusion of g-C₃N₄ NS reduced fiber diameter, improved wettability, increased mechanical properties, and biodegradability, while promoting bioactivity in MC3T3-E1 cells *in vitro*. This innovative approach underscores the versatility of g-C₃N₄ as a functional additive in tissue engineering, providing a viable path for addressing the limitations of conventional PCL scaffolds while enhancing bioactivity – a promising step toward bone regeneration. Therefore, the PCL NF/g-C₃N₄ NS-based nanocomposite holds promise for bone tissue engineering.

Stem cell therapy holds promise for treating various disorders in the human body. However, its efficacy is limited due to adverse effects or tissue damage during cell treatments. Injectable hydrogels, particularly nanohydrogels, have emerged as a solution to improve the engraftment and survival of injected stem cells.

Ghanbari *et al.* developed thermosensitive-based injectable hydrogels,⁸⁸ by incorporating oxidized alginate (OAlg), gelatin (Gel), and graphitic carbon nitride quantum dots (g-C₃N₄ QDs). These novel nanocomposites were investigated for tissue engineering. The mechanical, chemical, and physical properties of the hydrogel nanocomposites were analyzed, revealing improved mechanical strength with increased CNQDs content and an interconnected porous structure. *In-vitro*, degradation tests confirmed enhanced durability of the composites, as evidenced by decreased biodegradation and swelling ratios. Cell viability and attachment assays demonstrated the biocompatibility of the nanocomposite hydrogels, with over 88% viability and favorable cell adhesion to the osteosarcoma cell line MG63, attributed to the presence of CNQDs. The incorporation of CNQDs into hydrogels offers a highly promising solution for improving the mechanical and biological properties of injectable hydrogels, making them ideal candidates for advanced tissue engineering applications.

The regenerative potential of g-C₃N₄ and graphene oxide (GO) nanomaterials were evaluated for critical-sized bone defects.⁸⁹ *In-vitro*, cytotoxicity and hemocompatibility tests were conducted, along with the assessment of their ability to induce osteogenesis in human fetal osteoblast (hFOB) cells. *In vivo* experiments were performed in rabbits with femoral condyle bone defects, comparing control defects with

g-C₃N₄ or GO scaffolds. Evaluation at various time points revealed good cell viability, hemocompatibility, and enhanced expression of osteogenesis-related markers in hFOB cells for both materials. The g-C₃N₄ group showed complete healing of the bone defect, with higher percentages of osteoid tissue and mature collagen, increased biodegradation, and elevated expression of osteocalcin (OC) and osteopontin (OP). This study beautifully highlights the potential of g-C₃N₄ in regenerating critical-sized bone defects, demonstrating its robust osteogenic properties and paving the way for its application in complex bone repair scenarios. The results suggested that GO/g-C₃N₄ nanocomposites hold promise for critical size-based bone tissue engineering. The exceptional physicochemical and biological properties of two-dimensional (2D) nanomaterials have garnered significant attention in recent years, particularly in the field of tissue engineering.^{90,91}

A recent review provided an overview of various 2D nanomaterials and their advantages, focusing on graphitic carbon nitride-based nanomaterials' use in bone tissue engineering.⁹¹ The review discussed the numerous applications of these nanomaterials, including bone tissue engineering,^{87,91} as well as connective tissue and muscle, heart tissue,^{90,92} as mentioned in Fig. 10. The comprehensive nature of this review showcases the versatility of g-C₃N₄ in various tissue engineering domains, particularly in bone regeneration. It reinforces the importance of interdisciplinary research in leveraging the unique properties of 2D nanomaterials for advanced biomedical applications. The use of these nanomaterials in bone tissue engineering has been studied extensively, and the review highlighted their potential in enhancing bone regeneration.

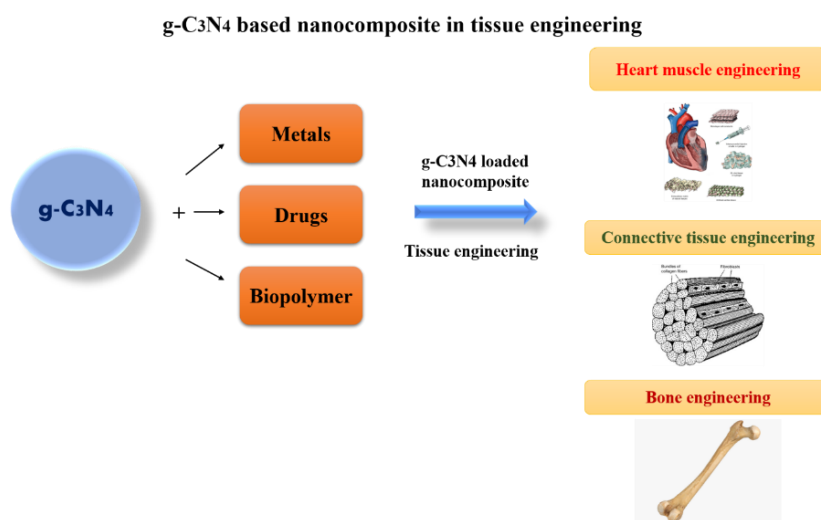


Fig. 10 – Applications of g-C₃N₄-based nanocomposites in tissue (bone, connective, and heart muscle) engineering.^{87,90–92}

Table 2

Applications of Graphitic Carbon Nitride (g-C₃N₄) in Various Fields

g-C ₃ N ₄ applications	Description	References
Catalysis	Advances in g-C ₃ N ₄ catalysts, including doping and novel composites, have enhanced photocatalytic applications like CO ₂ reduction, water splitting, and pollutant degradation. Techniques like 2D interfaces and nitrogen vacancies improve efficiency and address key challenges.	38 37
Energy Storage in Batteries	g-C ₃ N ₄ is a promising material for lithium-ion batteries due to its high conductivity, stability, and eco-friendly composition. Techniques like heteroatom refilling improve performance, achieving high capacity and excellent cycling stability.	51 52
Sensor	g-C ₃ N ₄ is highly versatile for use in sensors, offering enhanced sensitivity and selectivity for detecting biomolecules, heavy metals, and environmental pollutants.	62 63
Biomaterials	g-C ₃ N ₄ shows great potential in biomedical applications, including bioimaging, photodynamic therapy, and pH-responsive drug delivery, due to its biocompatibility and unique properties.	67
Anticancer Activity	g-C ₃ N ₄ nanomaterials show potential as efficient drug carriers for targeted and controlled anticancer drug delivery with minimal toxicity.	69 70
Antimicrobial Activity	g-C ₃ N ₄ -based nanomaterials demonstrate potent antimicrobial properties, photocatalytic activity, and environmental applications under visible-light irradiation.	85
Tissue Engineering	g-C ₃ N ₄ -based nanomaterials enhance scaffolds, hydrogels, and composites for improved biocompatibility, osteogenesis, and bone regeneration in tissue engineering.	89

CONFRONTS AND FUTURE PERSPECTIVE

Future investigations in the field of g-C₃N₄ nano-based materials should focus on the deliberate design and controlled synthesis of new nanostructures and their derivatives with specific morphological adjustments. Additionally, it is necessary to explore and assess effective modification techniques for g-C₃N₄ based on both experimental findings and theoretical calculations to enhance its photocatalytic efficiency. Finally, these materials can have versatile applications in various traditional and emerging domains, posing several challenges that need to be addressed.

- Creating g-C₃N₄ nano-based materials in a cost-effective and environmentally friendly manner requires a meticulous selection of precursors and heating processes. Among the precursors, urea stands out as a commonly used and less expensive option compared to melamine and dicyandiamide. Urea-based synthesis of g-C₃N₄ resulted in a material with a large specific surface area, which is desirable for various applications. Therefore, careful consideration of precursor selection can lead to a high-quality end product that is both economical and efficient. However, in order to achieve low-cost and green synthesis while also improving the photocatalytic performance of g-C₃N₄ nano-based materials, a trade-off may sometimes be necessary.
- Utilizing emerging machine learning and big data techniques, theoretical calculations and simulations are being conducted to discover new nano-based materials based on g-C₃N₄. To facilitate rapid searches for valuable modified g-C₃N₄, a database has been established related to g-C₃N₄ and its derivatives. By combining experimental and theoretical approaches, a comprehensive understanding of the relationship between the structure, morphology, and properties of modified g-C₃N₄ should be achieved, ultimately leading to enhanced catalytic efficiency.
- The potential of using g-C₃N₄ nano-based materials for commercial applications is yet to be fully realized. Although there have been numerous efforts to utilize g-C₃N₄ and its derivatives in diverse fields such as solar cells, sensors, pollutant degradation, and hydrogen generation, the majority of the research has been carried out in laboratory settings. However, there is a need for a significant advancement in the industrial application of g-C₃N₄ materials, which is highly anticipated. This indicates that despite the promising results obtained in the lab, additional research and development are required to bring g-C₃N₄-based products to the market and make them more widely available for industrial applications.

CONCLUSIONS

In recent decades, g-C₃N₄ emerged as a highly promising material for biomedical and nano technique applications. This 0-3D material attracted significant attention due to its remarkable stability, tunable bandgap, and excellent photocatalytic activity. These unique properties make it a versatile agent with great potential in various fields, including solar energy, energy conversion, environmental remediation, modern batteries, and electronics. Moreover, g-C₃N₄ gained attention in medical fields for its antioxidant, antimicrobial, anti-cancer, and biomedical properties. Despite these promising characteristics, g-C₃N₄ is still in the early stages of development, and further research is required to comprehend its potential and limitations fully. The ongoing exploration of this material is expected to yield valuable insights and open up new avenues for future applications. Overall, g-C₃N₄ represents a virtual, versatile, and efficient material with broad applicability, and its continued study is anticipated to thrive in the years to come.

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