# Green-Synthesized Metal Oxide–Carbon Nitride Nanocomposites for Photocatalytic Water Remediation: Progress Mechanisms and Future Perspectives

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## Abstract

The rapid escalation of water pollution caused by organic dyes, pharmaceuticals and pathogenic microorganisms has created an urgent demand for sustainable and efficient remediation strategies. Semiconductor-based photocatalysis has emerged as a promising solution due to its ability to achieve effective mineralization of persistent contaminants under mild operating conditions. Recent research has demonstrated that nanocomposite engineering offers significant advantages over single-component photocatalysts by enhancing visible-light absorption, suppressing charge recombination, and improving catalytic stability. In particular, graphitic carbon nitride (gCN) and sulfur-modified carbon nitride (SCN) have gained considerable attention owing to their metal-free nature, tunable electronic structure, and environmental compatibility. When integrated with metal oxide semiconductors, these materials form efficient heterojunction systems that promote interfacial charge transfer and reactive species generation. This review critically examines recent advances in the green-mediated synthesis, characterization, and photocatalytic performance of binary and ternary nanocomposites, incorporating gCN and SCN. Emphasis is placed on low-cost, scalable synthesis routes, structural and electronic modifications, mechanistic insights, and practical challenges associated with environmental remediation applications. The review further highlights existing research gaps and outlines, along with future directions, toward the development of high-performance sustainable photocatalysts for environmental remediation.

**Keywords:** Green synthesis; graphitic carbon nitride gCN; sulfur-doped carbon nitride SCN; metal oxide nanocomposites; heterojunction photocatalysis; Z-scheme charge transfer; visible-light activity; dye degradation; pharmaceutical removal; environmental remediation.

## 1. Introduction

Rapid industrialization, population growth, and expanding urbanization have led to a significant increase in environmental pollution, particularly in aquatic systems. Industrial effluents released from textile, pharmaceutical, chemical, and dye manufacturing sectors contain a wide range of organic contaminants, including synthetic dyes, antibiotics, and pharmaceutical residues. These pollutants are often chemically stable, toxic, and resistant to biodegradation, which results in their prolonged persistence in water bodies. Continuous discharge of untreated or partially treated wastewater poses serious risks to aquatic ecosystems and human health and also contributes to the deterioration of drinking water quality. Conventional wastewater treatment methods, such as coagulation, adsorption, filtration, and biological processes, often suffer from limitations including incomplete mineralization, secondary pollution generation, high operational costs, and limited effectiveness against recalcitrant compounds. In response to these limitations, advanced oxidation processes have gained considerable attention as effective alternatives for wastewater treatment due to their ability to generate highly reactive species capable of degrading persistent organic pollutants. Among these approaches, semiconductor-based photocatalysis has emerged as a promising technique because it operates under mild conditions and enables the mineralization of contaminants into

environmentally benign products. Photocatalytic processes utilize light energy to activate semiconductor materials, leading to the formation of reactive oxygen species that drive oxidative degradation reactions.

However, the practical application of conventional single-component photocatalysts remains constrained by rapid charge carrier recombination, limited visible light utilization, and insufficient surface activity. To overcome these drawbacks, the development of nanostructured materials and engineered nanocomposites has become an important research direction for achieving enhanced photocatalytic efficiency and long-term operational stability. Nanotechnology has provided new opportunities to address these challenges by enabling the design of materials with tailored structural and electronic properties at the nanoscale. Nanomaterials exhibit high surface area, enhanced reactivity, and tunable band structures, which significantly improve photocatalytic performance compared to their bulk counterparts. In particular, the formation of binary and ternary nanocomposites has proven effective in promoting charge separation, extending light absorption, and increasing the availability of active sites.

The synergistic interaction between different components within a nanocomposite can suppress electron-hole recombination and facilitate efficient interfacial charge transfer. As a result, nanocomposite-based photocatalysts demonstrate superior activity, stability, and recyclability, which are essential for practical wastewater treatment applications. Among the various photocatalytic materials explored, carbon nitride-based semiconductors have emerged as promising candidates due to their visible light activity, chemical stability, and metal-free nature. In particular, graphitic carbon nitride gCN and sulfur-modified carbon nitride SCN have attracted considerable attention owing to their suitable electronic structure, low cost, and environmentally benign characteristics. However, the photocatalytic performance of pristine gCN and SCN is often limited by rapid charge carrier recombination and insufficient surface activity. To overcome these limitations, coupling gCN and SCN with metal oxide semiconductors through the formation of heterojunction nanocomposites has proven to be an effective strategy. Such hybrid systems enable improved charge separation, enhanced redox capability, and efficient utilization of visible light, thereby significantly improving photocatalytic efficiency for pollutant degradation, as shown in Fig 1.
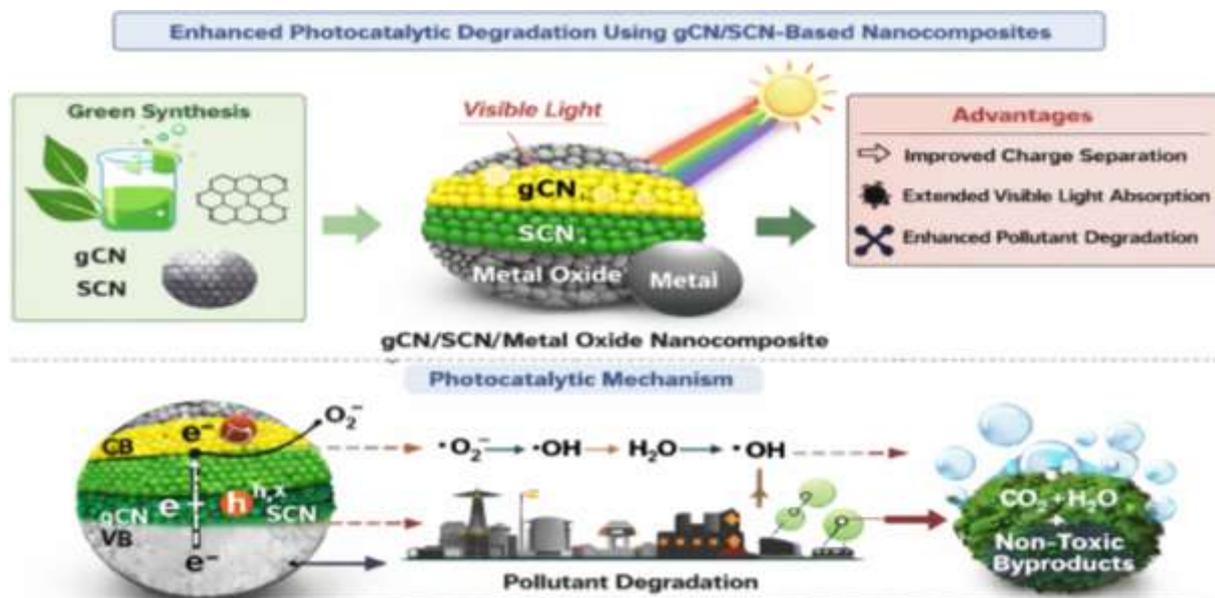


**Fig. 1**

Schematic illustration of gCN and SCN-based metal oxide nanocomposites for visible-light-driven photocatalytic pollutant degradation

In view of the growing interest in carbon nitride-based heterojunction systems, extensive research has been reported on the synthesis, modification, and applications of gCN- and SCN-coupled nanocomposites. The following chapter presents a critical review of the existing literature on green-mediated synthesis routes, structural and optical characteristics, photocatalytic performance, and mechanistic interpretations. This review establishes the scientific background, identifies key limitations, and highlights the research gaps addressed in the present work.

## 2. Overview and Scope of the Review

### 2.1 History and Background

This work reviews prior studies on the green synthesis, characterization, and environmental applications of binary and ternary nanocomposites, consistent with the objectives of the present research. Emphasis is placed on metal oxide systems coupled with graphitic carbon nitride (gCN) and sulfur-doped carbon nitride (SCN), synthesized via cost-effective routes such as co-precipitation, hydrothermal, microwave-assisted, and sol–gel methods. The literature addresses structural, optical, and surface properties, along with photocatalytic dye degradation, pharmaceutical removal, antibacterial activity and heterojunction- or Z-scheme-driven mechanisms.

**Siriwong et al. [1].**, have reported the synthesis and photocatalytic performance of doped metal oxide nanoparticles for environmental remediation applications. Various doped systems such as Fe-doped $TiO_2$, $WO_3$-doped ZnO and Fe-doped $CeO_2$ were prepared using modified sol–gel, flame spray pyrolysis and homogeneous precipitation methods. Structural and morphological properties were examined using XRD and TEM, while BET analysis confirmed enhanced surface areas. Photocatalytic activity was evaluated through the mineralization of organic pollutants under UV and visible light irradiation. The study demonstrated that metal ion doping significantly improves light absorption, charge separation efficiency, and photocatalytic performance compared to pristine metal oxides.

**Naseem and Durrani [2].**, have presented a comprehensive review highlighting the role of metal oxide nanoparticles in wastewater treatment and antibacterial applications. The authors emphasized that nanostructured metal oxides possess high surface area, tunable band gaps, and strong redox properties, enabling efficient removal of dyes, heavy metals, and pathogenic microorganisms. Antibacterial activity was mainly attributed to the generation of reactive oxygen species and membrane disruption mechanisms.

### 2.2 Synthesis Pathways For Nanocomposites

**Samrot et al. [3]** have reviewed green-synthesized nanoparticle-based polymer nanocomposites with a strong focus on eco-friendly synthesis strategies and sustainability. Biological resources such as plant extracts, polysaccharides, and bioactive compounds were employed as reducing and stabilizing agents for nanoparticle formation. The authors discussed synthesis techniques, structural characteristics, and functional properties of bio-reinforced nanocomposites. Applications in environmental remediation, biomedical devices, packaging, and industrial materials were highlighted. The study concluded that green synthesis routes significantly reduce toxicity and cost while enhancing environmental compatibility, making these nanocomposites promising for sustainable nanotechnology applications.

**Praveen Kumar et al. [4]** have investigated binary metal oxide nanocomposites, including $MnO_2$–ZnO, $Fe_2O_3$–ZnO, NiO–ZnO, and $CeO_2$–ZnO, synthesized through precipitation-pyrolysis methods. Structural and textural characterization using XRD, SEM-EDX, TEM, and nitrogen adsorption revealed mesoporous architectures with surface areas ranging from 76 to 134 $m^2$ $g^{-1}$. These binary nanocomposites exhibited superior catalytic and adsorption performance compared to individual metal oxides. The enhanced activity was attributed to synergistic interactions between the oxide components and the presence of Lewis acid–base active sites, validating the effectiveness of binary metal oxide nanocomposite design.

**Girish Kumar and Rao [5].**, have provided an extensive review on tungsten-based nanomaterials such as $WO_3$ and $Bi_2WO_6$, focusing on charge carrier transfer mechanisms and photocatalytic applications. The review discussed various modification strategies including heterojunction formation, metal doping and surface engineering to suppress electron–hole recombination. Enhanced visible-light absorption and prolonged charge carrier lifetime were identified as key factors contributing to improved photocatalytic performance. Applications in wastewater treatment and organic pollutant degradation were highlighted,

establishing tungsten-based nanocomposites as promising alternatives to conventional TiO$_2$-based photocatalysts.

## 2.3 Emphasis on mixed metal oxide nanocomposites

**Han et al. [6].**, have systematically investigated the physical and structural properties of various aluminate spinels, including MgAl$_2$O$_4$, CoAl$_2$O$_4$, NiAl$_2$O$_4$, CuAl$_2$O$_4$, and ZnAl$_2$O$_4$

**Table 1.** Comparison of wastewater treatment methods and rationale for the preference of advanced oxidation-based photocatalysis

| Method | Main advantage | Main limitation | Outcome type | Suitability for recalcitrant pollutants |
|---|---|---|---|---|
| **Coagulation and flocculation** | Simple operation and low initial cost | Generation of large sludge volume and incomplete removal of dissolved pollutants | Phase transfer | Low |
| **Adsorption** | High removal efficiency at ambient conditions and ease of operation | Secondary waste generation and limited regeneration efficiency | Phase transfer | Moderate |
| **Membrane filtration** | High quality treated water and potential for reuse | High capital cost membrane fouling and frequent maintenance | Phase separation | Moderate |
| **Biological treatment** | Environmentally benign process and low energy requirement | Ineffective for stable toxic compounds and slow degradation kinetics | Partial transformation | Low |
| **Chemical oxidation** | Capable of degrading a wide range of contaminants | High chemical consumption and possible formation of byproducts | Partial destruction | Moderate |
| **Photocatalysis AOP** | Complete mineralization under mild conditions and utilization of light energy | Catalyst recovery and scale up challenges | Destruction and mineralization | High |

synthesized via a solution combustion method followed by calcination. XRD and XPS analyses confirmed the formation of pure spinel phases with good crystallinity, while SEM revealed porous nanoparticle morphologies. Optical properties evaluated through UV–visible spectroscopy showed variation in band gap energies depending on cation distribution. The study also discussed anti-site disorder and magnetic behavior, establishing aluminate spinels as structurally stable platforms with tunable electronic properties for catalytic and environmental applications.

**Kaci et al. [7].**, have reported the synthesis of spinel $CuAl_2O_4$ nanoparticles using a co-precipitation route and examined their optical, electrochemical and photocatalytic properties. XRD confirmed cubic spinel structure, while TEM revealed nanosized spherical particles. Diffuse reflectance spectroscopy was employed to determine optical constants and band gap energy. The photocatalytic performance was evaluated through sunlight-driven degradation of methyl violet dye, achieving nearly 89% removal within 3 h. Reactive species analysis indicated the involvement of hydroxyl and superoxide radicals. The catalyst also demonstrated good recyclability, highlighting $CuAl_2O_4$ spinel as an efficient visible-light-active photocatalyst.

## 2.4 Impact of gCN/SCN doping

**Prabavathi et al. [8].**, have constructed a hetero-structured $CoWO_4/g\text{-}C_3N_4$ nanocomposite via a hydrothermal method followed by ultrasonication for visible-light-driven photocatalytic degradation of norfloxacin. Structural and morphological analyses using XRD, TEM, EDX, and XPS confirmed uniform anchoring of $CoWO_4$ nanoparticles on $g\text{-}C_3N_4$ nanosheets. The nanocomposite exhibited significantly enhanced photocatalytic activity compared to pristine components, achieving high degradation efficiency with good stability over multiple cycles. Radical scavenging experiments revealed dominant involvement of reactive oxygen species, while a Z-scheme charge transfer mechanism was proposed to explain the improved photocatalytic performance.

**Amritha and Badhulika [9].**, have fabricated a $ZnWO_4/CoWO_4$ heterojunction on a flexible substrate for multispectral photodetection applications. $CoWO_4$ thin films were deposited using the SILAR technique, while $ZnWO_4$ nanoparticles synthesized via co-precipitation were drop-casted to form the heterojunction. Structural and morphological characterization confirmed intimate interfacial contact between the two tungstate phases.

The heterostructure exhibited broadband photo-response spanning the UV to infrared regions due to complementary band gaps. This work demonstrated the versatility of tungstate-based nanocomposites and their potential beyond photocatalysis, extending into optoelectronic and sensing applications.

**Kumar and Rao [10].**, have emphasized the role of tungsten-based nanomaterials, particularly $WO_3$ and related tungstate composites, in photocatalytic and environmental applications. The authors discussed intrinsic limitations such as fast charge recombination and low reduction potential, followed by strategies including heterojunction formation with cobalt and other transition metals. Improved charge separation and extended visible-light absorption were identified as key factors enhancing photocatalytic efficiency. Applications in wastewater remediation and organic pollutant degradation were highlighted. The review established tungstate-based nanocomposites as promising candidates for next-generation visible-light-driven catalytic systems.

## 2.5 Improved photocatalysis attributed to green mediation – Dye Degradation

**Sathiyavimal et al. [11].**, have reported an eco-friendly green synthesis of CuO nanoparticles using *Psidium guajava* leaf extract and evaluated their antibacterial and photocatalytic performance. Structural confirmation using XRD revealed monoclinic CuO, while FE-SEM and HR-TEM indicated nanoscale particles with varied morphologies. The biosynthesized CuO nanoparticles exhibited strong antibacterial activity against both Gram-positive and Gram-negative bacteria. Photocatalytic degradation studies demonstrated efficient removal of Congo red and methylene blue dyes under sunlight irradiation. The

enhanced performance was attributed to surface functionalization by phytochemicals, which improved charge separation and reactive oxygen species generation.

**Kamaraj et al. [12].,** have fabricated a $CuO–Pb_2O_3$ p–n heterojunction photocatalyst using a simple wet chemical route and investigated its visible-light photocatalytic activity. XRD, SEM, TEM, BET and XPS analyses confirmed successful heterojunction formation with enhanced surface area and light absorption. The $CuO–Pb_2O_3$ nanocomposite exhibited nearly two-fold higher photocatalytic degradation efficiency toward Rose Bengal dye compared to individual oxides. Kinetic studies revealed a higher reaction rate constant, attributed to improved charge carrier separation at the p–n interface. The work highlighted copper-based heterostructures as effective visible-light photocatalysts.

**Table 2**. *Major classes of water pollutants, their sources, associated risks and representative examples*

| Pollutant category | Typical sources | Main concerns | Common examples used in studies | Representative references |
|---|---|---|---|---|
| **Dyes** | Textile, dyeing units, leather processing, industries, paper and printing sectors | High toxicity, visual pollution, persistence in aquatic systems and resistance to biodegradation | Rose Bengal, Rhodamine B, Methyl Orange, Methylene Blue | [1–4] |
| **Pharmaceuticals** | Hospital effluents, pharmaceutical manufacturing units, domestic sewage | Bioaccumulation, endocrine disruption, antimicrobial resistance and chronic toxicity | Tetracycline, Diclofenac, Ciprofloxacin, Ibuprofen | [5–8] |
| **Pathogenic microorganisms** | Domestic, sewage, hospital, wastewater livestock and municipal discharges | Waterborne diseases, spread of infections and public health risks | Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa | [9–11] |

**Han et al. [13].,** have synthesized a series of aluminate spinels including $NiAl_2O_4$, $CuAl_2O_4$, $CoAl_2O_4$, $ZnAl_2O_4$ and $MgAl_2O_4$ using a solution combustion method followed by controlled calcination. XRD and XPS confirmed pure spinel phase formation, while SEM analysis showed porous nanostructured morphologies. Optical studies revealed tunable band gaps influenced by cation distribution and anti-site disorder.

The authors further discussed magnetic and thermal properties, emphasizing the stability and multifunctional nature of aluminate spinels. This study provided a fundamental understanding of spinel-based nanomaterials for catalytic and environmental applications.

**Gholami et al. [14].**, have reported the green synthesis of $NiAl_2O_4/NiO$ nanocomposites using plant-based extracts as precipitating agents, followed by thermal decomposition. Structural and morphological characterization using XRD, SEM, TEM and BET confirmed porous nanostructures with enhanced surface area. Optical analysis showed tunable band gap energies depending on calcination temperature. Electrochemical hydrogen storage performance was evaluated, revealing improved discharge capacity with optimized synthesis conditions. The study demonstrated that green synthesis routes not only reduce environmental impact but also enhance the functional properties of nickel-based nanocomposites.

## 2.6 Enhanced hetetrojunction formation – Drug Degradation

**Chellammal Gayathri et al. [15].**, have investigated the effect of synthesis methodology on the photocatalytic activity of $NiAl_2O_4$ nanoparticles prepared via sol–gel and co-precipitation routes. XRD and BET analyses revealed that co-precipitated $NiAl_2O_4$ synthesized at higher pH exhibited smaller crystallite size and significantly larger surface area. Photocatalytic degradation studies using tetracycline and methylene blue demonstrated superior activity for co-precipitated samples, achieving high degradation efficiency within short irradiation time. The enhanced performance was attributed to improved surface area, optimized band gap and reduced electron–hole recombination.

**Rasheed et al. [16].**, have reported the synthesis of $ZnO@g-C_3N_4$ nanocomposites using a facile thermal decomposition strategy derived from ZIF-8 precursors. Comprehensive characterization using XRD, FT-IR, SEM, XPS, PL and EIS confirmed successful coupling and narrowed band gap. The optimized composite exhibited enhanced visible-light absorption and efficient charge separation. Photocatalytic studies demonstrated high degradation efficiency of tetracycline hydrochloride under visible light, outperforming pristine ZnO and $g-C_3N_4$. Recyclability tests confirmed good stability over multiple cycles. The enhanced performance was attributed to synergistic interfacial interaction and suppressed electron–hole recombination.

**Vasu et al. [17].**, have developed oxygen-doped graphitic carbon nitride (O-gCN) nanosheets via a simple thermal decomposition method using urea and oxalic acid. Structural and optical analyses revealed porous morphology and extended visible-light absorption due to oxygen incorporation into the gCN framework. The O-gCN photocatalyst exhibited superior degradation of Rhodamine B under visible light compared to pristine gCN. Radical trapping experiments confirmed the dominant role of reactive oxygen species in the degradation pathway. The study highlighted the effectiveness of non-metal doping in enhancing photocatalytic efficiency through band structure modulation.

**Isa et al. [18].**, have investigated ZnO/gCN heterojunction photocatalysts for simultaneous degradation of mixed dye systems. Structural characterization confirmed successful incorporation of $g-C_3N_4$ into the ZnO matrix, forming an effective heterojunction. Photocatalytic studies revealed enhanced degradation rates for multiple dyes, including Rhodamine B and methylene blue, under visible-light irradiation. The optimal gCN loading improved charge carrier separation and reduced recombination losses. The study demonstrated that ZnO-based heterostructures are promising candidates for complex textile wastewater treatment involving multiple organic dyes.

## 2.7 Improved synergistic redox behavior – Antimicrobial activiity

**Shoran et al. [19].**, have synthesized $CeO_2/g-C_3N_4$ nanocomposites via an ultrasonication-assisted method and evaluated their photocatalytic and antibacterial properties. XRD, UV–Vis and FT-IR analyses confirmed strong interfacial coupling between $CeO_2$ and $g-C_3N_4$. The optimized composite exhibited enhanced visible-light-driven degradation of Rose Bengal and crystal violet dyes compared to individual components. Antibacterial studies demonstrated effective inhibition against both Gram-positive and Gram-

negative bacteria. The enhanced activity was attributed to improved charge separation and synergistic redox behavior of the heterojunction.

**Kamaraj et al. [20].,** have fabricated $CuO-Pb_2O_3$ heterojunction photocatalysts using a wet chemical approach and studied their visible-light photocatalytic performance. Structural and optical analyses confirmed the formation of a p–n junction with enhanced light absorption. The nanocomposite showed significantly higher degradation efficiency for Rose Bengal dye compared to pristine CuO and $Pb_2O_3$. Kinetic analysis revealed an increased reaction rate constant due to efficient charge carrier separation at the heterointerface. The study emphasized the importance of heterojunction engineering for improving visible-light-driven dye degradation.

**Chen et al. [21].,** have constructed $CuAl_2O_4/g-C_3N_4$ p–n heterojunction photocatalysts via a self-assembly strategy to enhance visible-light-driven degradation of tetracycline hydrochloride. Structural and morphological analyses confirmed intimate interfacial contact between $CuAl_2O_4$ nanoplates and $g-C_3N_4$ nanosheets. The optimized heterojunction achieved nearly 90% degradation within 60 min under visible light and showed excellent stability over repeated cycles. Radical trapping and EPR studies revealed that superoxide radicals and photogenerated holes played dominant roles. The improved activity was attributed to efficient charge separation driven by the p–n junction architecture.

**Lv et al. [22].,** have reported copper-doped tubular graphitic carbon nitride synthesized through in-situ hydrolysis and self-assembly methods for visible-light-driven degradation of ibuprofen. Structural characterization revealed increased surface area and pore volume, while optical studies showed a narrowed band gap. The Cu-modified tubular $g-C_3N_4$ exhibited significantly enhanced photocatalytic degradation compared to pristine $g-C_3N_4$.

**Table 3.** Comparison of photocatalyst systems used for visible-light-driven dye degradation

| Photocatalyst system | Model pollutant | Light source | Degradation level | Dominant mechanism | Representative references |
|---|---|---|---|---|---|
| **Pristine metal oxides** | Rhodamine B Methyl Orange | UV or visible | Moderate | Fast charge recombination | [1–3] |
| **gCN or SCN** | Methylene Blue Rose Bengal | Visible | Moderate | Limited redox capability | [4–6] |
| **Metal oxide/gCN** | Rose Bengal Rhodamine B | Visible | High | Heterojunction charge separation | [7–10] |
| **Metal oxide/SCN** | Methyl Orange pharmaceuticals | Visible | High | Sulfur-modulated surface activity | [11–13] |
| **$CoWO_4$/gCN** | Rose Bengal | Visible | Very high | Z-scheme $\bullet O_2^-$ driven pathway | [14–16] |
| **$CuAl_2O_4$/gCN** | Methylene Blue | Visible | High | Suppressed recombination | [17–19] |
| **$NiAl_2O_4$/SCN** | Mixed dyes pharmaceuticals | Visible | High | Synergistic redox activity | [20–22] |

Mechanistic investigations identified superoxide radicals as the primary reactive species. Density functional theory calculations further supported the activation of ibuprofen molecules, demonstrating the effectiveness of doped carbon nitride systems for pharmaceutical pollutant remediation.

**Prabavathi et al. [23].,** have developed $CoWO_4/g-C_3N_4$ heterostructured photocatalysts using a hydrothermal method followed by ultrasonication for efficient degradation of norfloxacin under visible

light. XRD, TEM, XPS and EDX analyses confirmed uniform dispersion of $CoWO_4$ nanoparticles on g-$C_3N_4$ sheets. The composite showed significantly higher degradation efficiency compared to individual components and maintained good recyclability. Radical scavenging studies indicated the involvement of reactive oxygen species and a Z-scheme charge transfer mechanism was proposed. The work demonstrated the potential of cobalt-tungstate-based heterojunctions for antibiotic removal.

**Dharani et al. [24].**, have synthesized $CoFe_2O_4$/g-$C_3N_4$ nanocomposites using a sol–gel method assisted by ultrasonication and evaluated their visible-light photocatalytic performance toward Rhodamine B degradation. Structural analyses confirmed phase coexistence and reduced crystallite size, while UV–visible studies indicated band gap narrowing. The nanocomposite exhibited significantly higher degradation efficiency compared to pure $CoFe_2O_4$ and g-$C_3N_4$. Enhanced activity was attributed to improved charge separation and effective generation of hydroxyl radicals. This study highlighted the role of ferrite-based g-$C_3N_4$ composites in visible-light photocatalysis.

**Table 4.** Design rationale and functional advantages of metal oxide–carbon nitride nanocomposites for environmental remediation

| Material system | Metal oxide role | Carbon nitride role | Expected charge transfer | Dominant reactive species | Target application |
|---|---|---|---|---|---|
| **Metal oxide/gCN** | Structural stability and redox activity | Visible light response and surface functionality | Heterojunction-assisted separation | $\bullet O_2^-$ dominant with $h^+$ and $\bullet OH$ secondary | Dye and pharmaceutical degradation |
| **Metal oxide/SCN** | Enhanced electronic conductivity | Sulfur induced defect states | Improved interfacial charge mobility | $\bullet O_2^-$ dominant | Dye degradation and antimicrobial activity |
| **CoWO₄/gCN** | Narrow band gap and strong oxidation ability | Efficient electron transport | Z scheme pathway with suppressed recombination | $\bullet O_2^- \gg h^+ > \bullet OH$ | Persistent dye degradation |

| $CuAl_2O_4/gCN$ | Mixed valence redox centers | Extended visible absorption | Heterojunction driven charge separation | $\bullet O_2^-$ dominant with $h^+$ contribution | Pharmaceutical pollutant removal |
|---|---|---|---|---|---|
| $NiAl_2O_4/SCN$ | Chemical robustness and surface reactivity | Sulfur mediated charge modulation | Enhanced carrier lifetime | $\bullet O_2^-$ dominant | Antimicrobial and wastewater treatment |

**Shanmuganathan et al. [25].**, have fabricated $Co_3O_4@ZrO_2$ core–shell nanoparticles via a sol–gel route and investigated their antibacterial and photocatalytic properties. Structural and optical characterization confirmed core–shell architecture with enhanced stability. The nanocomposites exhibited strong antibacterial activity against both Gram-positive and Gram-negative bacteria. Photocatalytic degradation studies showed effective removal of Rhodamine B under visible light irradiation. The multifunctional behavior was attributed to synergistic interactions between the core and shell components, making these materials suitable for combined environmental remediation and antimicrobial applications.

**Venkataramana et al. [26].**, have investigated the photocatalytic degradation of polyethylene microplastics using $NiAl_2O_4$ spinel nanoparticles synthesized via co-precipitation and hydrothermal methods. Structural and surface analyses confirmed crystalline spinel formation with suitable optical properties. Photocatalytic experiments revealed effective degradation of polyethylene sheets under light irradiation, with hydrothermally synthesized $NiAl_2O_4$ showing higher degradation efficiency and noticeable weight loss within a few hours. FT-IR analysis confirmed chemical bond scission in the polymer matrix after treatment. The study highlighted the potential of nickel aluminate spinels as functional photocatalysts for addressing emerging microplastic pollution.

**Pirsaheb et al. [27].**, have reported the green synthesis of $NiAl_2O_4/NiO$ nanocomposites using olive leaf extract and evaluated their electrochemical hydrogen storage performance. Structural characterization using XRD, SEM and BET confirmed porous nanostructures with enhanced surface area. The incorporation of polymeric surfactants significantly improved hydrogen storage capacity and coulombic efficiency over repeated charge–discharge cycles. The study demonstrated that green synthesis routes not only reduce environmental impact but also enhance electrochemical performance. This work established nickel-based spinel nanocomposites as promising multifunctional materials linking energy storage with sustainable nanomaterial synthesis.

**Gholami et al. [28].**, have synthesized $NiAl_2O_4/NiO$ nanocomposites via a green thermal decomposition method using plant-derived extracts as precipitating agents. Detailed structural, optical and morphological analyses confirmed the formation of porous nanocomposites with tunable properties depending on calcination temperature. Electrochemical studies revealed that optimized samples exhibited improved hydrogen storage capacity and cycling stability. The work emphasized the role of green chemistry in tailoring nanocomposite properties while maintaining functional performance. These findings further support the versatility of nickel aluminate systems for energy-related and environmental applications.

**Kumar and Gedam et al. [29].**, have developed Cu and Ni co-doped ZnO photocatalysts using a facile co-precipitation method and examined their visible-light-driven photocatalytic and antimicrobial properties. Structural and spectroscopic analyses confirmed successful co-doping and reduced band gap energy. The optimized co-doped system exhibited significantly enhanced degradation efficiency toward organic dyes

compared to singly doped and pristine ZnO. Antimicrobial studies demonstrated effective inhibition of bacterial growth against both Gram-positive and Gram-negative strains. The enhanced performance was attributed to synergistic effects of dual dopants improving charge separation and reactive species generation.

**Wang et al. [30].**, have fabricated nano-$CuAl_2O_4$ spinel materials for copper stabilization and antibacterial applications. Controlled synthesis conditions yielded well-defined nanostructures with minimal copper leaching, addressing environmental toxicity concerns associated with copper-based agents. Antibacterial studies demonstrated significant inhibition of *Escherichia coli*, confirming long-term antimicrobial efficacy. The study emphasized the dual functionality of $CuAl_2O_4$ spinels in environmental protection and public health applications. This work concluded that stabilized spinel nanocomposites represent a promising class of multifunctional materials for sustainable environmental remediation and antimicrobial technologies.

## 3. Conclusion

The reviewed studies reveal that, despite progress in gCN- and SCN-based nanocomposites, systematic investigations into green-synthesized ternary systems and dopant-induced interfacial effects remain limited. Comparative structure–property–performance analyses and multifunctional evaluations integrating photocatalytic, antibacterial and pharmaceutical degradation activities are insufficiently explored. These gaps highlight the necessity for scalable, eco-friendly synthesis strategies supported by comprehensive characterization. The present research addresses these limitations through the development of low-cost, green-fabricated binary and ternary nanocomposites incorporating gCN and SCN for enhanced environmental remediation.

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