Article

Synergistic Photocatalysis of Metal Oxide-Decorated Graphene Oxide Nanocomposites for Industrial Dye Degradation: A Mini-Review

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Abstract

Rapid industrialisation has led to the extensive discharge of synthetic dyes into aquatic ecosystems, posing severe environmental and health hazards. While nanotechnology-based photocatalysis offers an efficient route for pollutant mineralisation, pure metal oxides often suffer from rapid charge recombination. This mini-review aims to evaluate the synergistic integration of graphene oxide with metal oxide nanoparticles, such as ZnO, Fe_3O_4, CdO, and TiO_2, to overcome these limitations. The primary objectives of this review are to summarise recent synthesis strategies, elucidate the photocatalytic mechanisms that enhance electron–hole separation, and analyse the degradation efficiency of persistent organic dyes. The graphene oxide framework provides an exceptional surface area and abundant functional groups that facilitate strong semiconductor interactions and rapid charge transport. This review also discusses current challenges regarding toxicity and scalability, and provides future perspectives for the development of sustainable wastewater remediation technologies.

Keywords: graphene oxide; metal oxide nanoparticles; photocatalytic dye degradation; hybrid nanocomposites; wastewater remediation

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Introduction

Nanotechnology is an emerging field of science that deals with the design, synthesis and application of materials at the nanoscale, typically between 1 and 100 nanometres [1]–[5]. At this scale, materials exhibit unique physical, chemical and biological properties, such as enhanced reactivity, surface area, and quantum effects, which differ significantly from their bulk counterparts [6]–[8]. These distinctive features have enabled wide-ranging applications across multiple disciplines, such as medicine (drug delivery, diagnostics and cancer therapy), environmental remediation (water purification and pollutant degradation), energy (solar cells and energy storage) and agriculture (nanofertilisers and pest control) [9]–[13]. As research continues to advance, nanotechnology is expected to play a crucial role in addressing global challenges related to health, sustainability and industrial development. Water contamination caused by industrial effluents has become one of the most pressing environmental challenges in modern society. The rapid expansion of textile, pharmaceutical, paper, leather and dye manufacturing industries has resulted in the release of large quantities of coloured wastewater into natural water bodies [14], [15]. Synthetic dyes are extensively used owing to their high stability, strong coloration properties and resistance to fading. However, these same characteristics make them persistent environmental pollutants once they enter aquatic ecosystems [16].

Synthetic dyes are typically composed of complex aromatic molecular structures containing azo, anthraquinone, or triphenylmethane groups. These chemical structures are designed to resist photodegradation, oxidation and microbial attack, which makes them difficult to remove through conventional wastewater treatment methods [17]. Therefore, dye molecules remain stable in water bodies for extended periods, leading to environmental pollution and ecological imbalance as shown in Figure 1.

Even at low concentrations, dyes have a significant impact on aquatic environments by reducing light penetration. This reduction inhibits photosynthesis in aquatic plants and algae, which disrupts oxygen production and destabilises the entire aquatic food chain. In addition, many synthetic dyes and their degradation intermediates are toxic, mutagenic and potentially carcinogenic. Prolonged exposure to dye-contaminated water poses serious health risks to humans and animals, ranging from skin irritation to systemic toxicity [18]. Conventional treatment techniques such as coagulation, flocculation, membrane filtration, adsorption and biological treatment have been widely applied for dye removal [19]–[21]. However, these methods often have limitations, including incomplete dye removal, high operational costs, and the generation of secondary pollutants. Consequently, there is growing interest in developing advanced technologies capable of completely mineralising organic pollutants in wastewater [22].

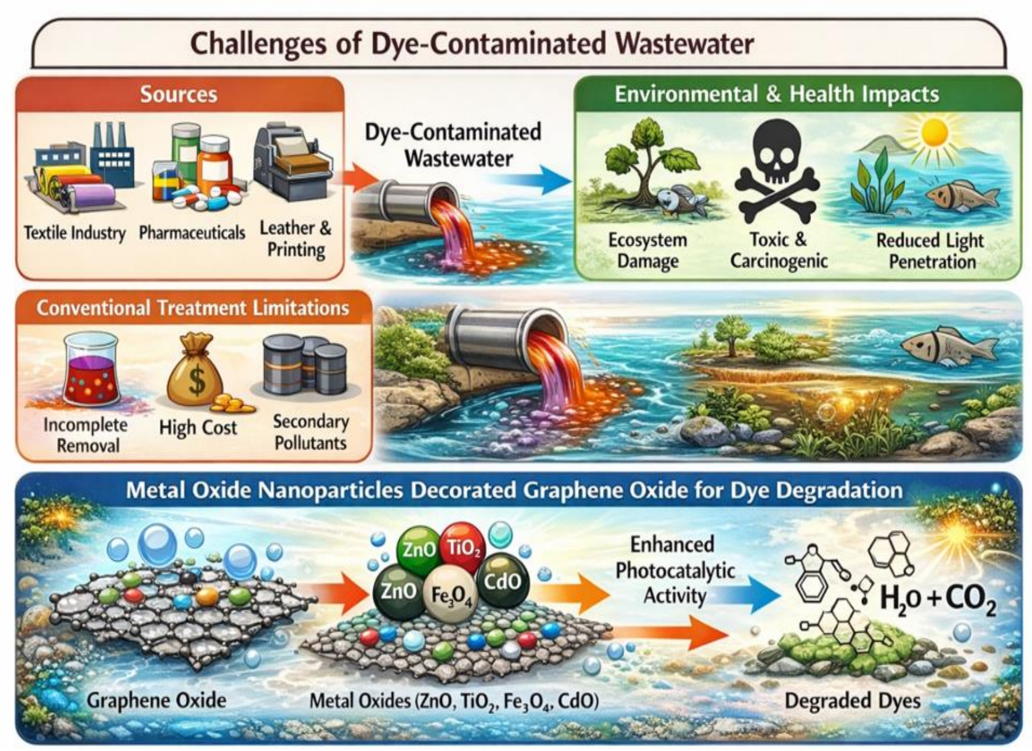

Figure 1: Schematic representation of environmental impacts of dye-contaminated wastewater and the mechanism of photocatalytic degradation by metal oxide-decorated graphene oxide nanocomposites

Advanced oxidation processes (AOPs) have emerged as highly effective techniques for the degradation of persistent organic contaminants [23]. These processes rely on the generation of highly reactive oxygen species, such as hydroxyl radicals and superoxide radicals, which possess strong the oxidative potential to break down complex organic molecules into harmless end products [24]. Among the various AOPs, semiconductor photocatalysis has gained considerable attention owing to its environmental compatibility and potential for use in solar energy [25].

Photocatalytic degradation involves the use of semiconductor materials that absorb light and generate electron–hole pairs to initiate oxidation-reduction reactions [26]. Metal oxide nanoparticles such as zinc oxide (ZnO), nickel oxide (NiO), nickel zinc ferrite ($NiZnFe_2O_4$) titanium dioxide (TiO_2), nickel ferrite (NiFe2O4), zinc ferrite ($ZnFe_2O_4$), iron oxide (Fe_3O_4), and cadmium oxide (CdO) are widely used photocatalysts because of their favourable electronic structures, chemical stability and relatively low cost [27]–[31]. Despite these advantages, pure metal oxides often exhibit limited efficiency owing to rapid recombination of photogenerated charge carriers and a limited surface area for pollutant adsorption. In addition, many metal oxides require ultraviolet light for activation, which constitutes only a small portion of the solar spectrum [32].

To overcome these limitations, researchers have explored hybrid nanocomposites that combine metal oxide nanoparticles with carbon-based nanostructures. Graphene oxide (GO) has emerged as an excellent candidate for this purpose owing to its unique structural, chemical and electronic properties [33]–[35]. The integration of metal oxide nanoparticles with GO significantly improves performance by enhancing charge separation, increasing adsorption capacity, and promoting efficient electron transport.

Although recent studies have explored various GO-based hybrids, there remains a lack of consolidated analysis focusing specifically on the synergistic electronic transitions between diverse metal oxides and the GO framework for industrial dye remediation. This mini-review aims to fill this gap by evaluating recent advancements (2021–2026) in synthesis and performance. The primary objective is to elucidate how these synergistic interactions can be optimised to develop high-efficiency, sustainable materials for complete pollutant mineralisation. This work is structured as a mini-review, and focuses on the latest advancements from 2021 to 2026. By narrowing the scope to the synergistic electronic interactions between GO and specific metal oxide semiconductors, this review provides a concise yet high-density analysis of the most recent breakthroughs in industrial dye remediation.

Review Methodology

The present review was developed through a structured three-phase systematic survey to ensure a comprehensive and up-to-date analysis of metal oxide-decorated GO nanocomposites.

2.1 Database Selection and Search Strategy

A systematic search was executed across major scientific repositories, including Scopus, Web of Science, Google Scholar and ScienceDirect. It covered literature from 2011 to 2026. The search strategy used Boolean operators with key terms: ("Graphene Oxide" OR "GO") AND ("Metal Oxide Nanoparticles" OR "MONPs") AND ("Photocatalysis" OR "Dye Degradation"). This search focused primarily on high-impact factor journals in the fields of nanotechnology, environmental science, and materials chemistry.

2.2 Inclusion and Quality Assessment

To maintain the technical rigour of this mini-review, over 150 records were initially screened. Articles were selected based on specific inclusion criteria, where priority was given to articles published within the last five years (2021-2026) to capture the latest synthesis trends. Only studies providing verifiable characterisation, such as XRD, SEM/TEM, and XPS, were included. Finally, studies had to provide quantitative kinetic data, including degradation rates or percentage efficiency, for common organic dyes such as Methylene Blue (MB) or Rhodamine B (RhB).

2.3 Information Synthesis

A total of 72 key sources were selected for final analysis. The data were synthesised by categorising the nanocomposites based on their active metal oxide component (ZnO, TiO_2, Fe_3O_4, and CdO). This allowed for a comparative meta-analysis of how different semiconductor bandgaps interact with the GO framework to suppress electron–hole recombination and enhance overall photocatalytic performance under UV and visible light.

Graphene Oxide as a Functional Nanomaterial

Graphene oxide is a two-dimensional carbon-based nanomaterial derived from graphite through oxidation processes such as the modified Hummers method. During this process, graphite layers are chemically oxidised, resulting in the introduction of oxygen-containing functional groups onto the carbon lattice [36]. These functional groups include hydroxyl, epoxy, carbonyl and carboxyl groups, which significantly alter the physicochemical properties of the material [37].

One of the most remarkable features of GO is its extremely high surface area, which can reach several hundred square metres per gram [38]. This large surface area provides abundant active sites for adsorption and catalytic reactions. In photocatalytic applications, the large surface area facilitates the adsorption of dye molecules onto the catalyst surface, which increases the efficiency of degradation reactions [39].

The presence of oxygen-containing functional groups also makes GO highly hydrophilic and dispersible in aqueous solutions [40].This property enables the formation of stable suspensions and promotes strong interactions between GO and metal oxide nanoparticles [41]. The functional groups can act as anchoring sites for metal ions, allowing uniform deposition of nanoparticles on the GO surface as shown in Figure 2.

Although pristine graphene is a zero-bandgap semiconductor with exceptional conductivity owing to its continuous sp^2-hybridised carbon network, the oxidation process disrupts this conjugation. The introduction of oxygen functional groups creates sp^3-hybridised carbon atoms, which effectively transform GO into an electrical insulator or wide-bandgap semiconductor, depending on the degree of oxidation [42]. However, GO still contains residual sp^2 clusters that facilitate localised electron mobility, providing sufficient pathways for electron transport during photocatalytic reactions [43].When metal oxide nanoparticles are coupled with GO, photogenerated electrons can rapidly transfer from the semiconductor to the conductive domains of the GO sheets

[44]. This electron transfer process reduces the recombination of electron–hole pairs and prolongs the lifetime of charge carriers, which enhances photocatalytic efficiency.

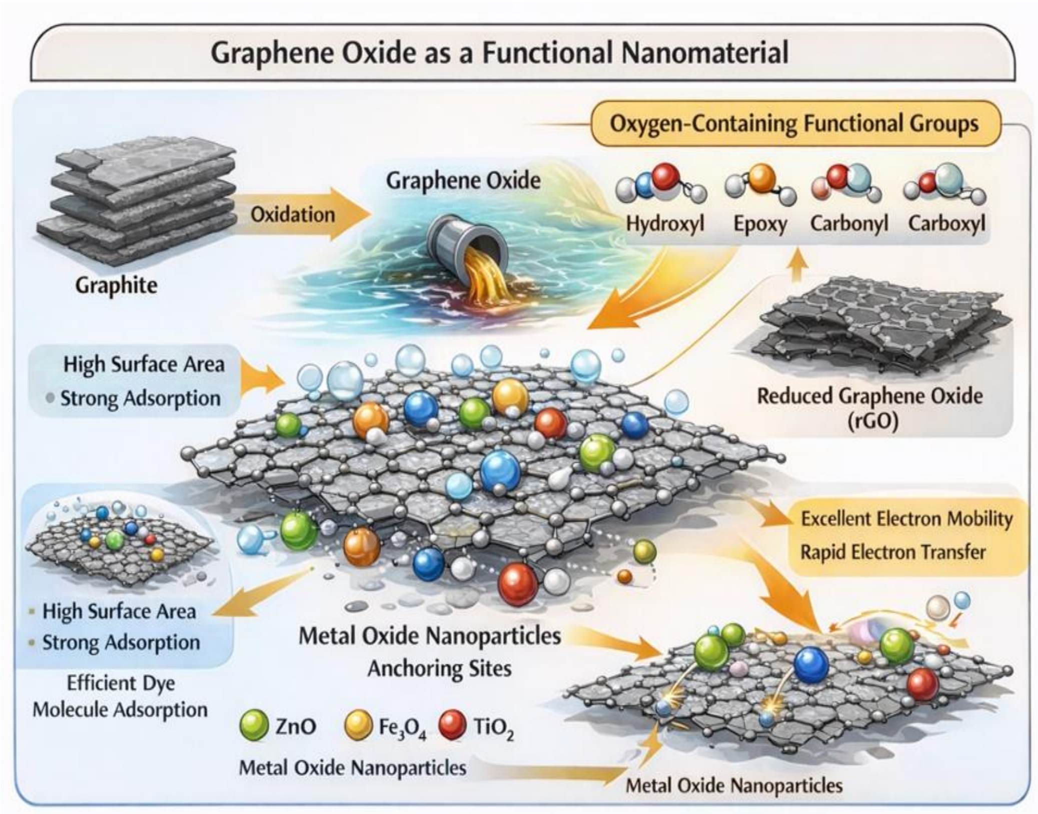

Figure 2: Schematic representation of graphene oxide as a functional nanomaterial enabling metal oxide nanoparticle anchoring for enhanced adsorption and electron transfer

Graphene oxide also exhibits strong adsorption capability towards aromatic compounds due to π–π stacking interactions between the conjugated carbon structure and aromatic dye molecules. These interactions allow dye molecules to accumulate near catalytic active sites on the nanocomposite surface. As a result, the probability of photocatalytic reactions increases, which leads to faster degradation rates [45].

In addition, GO can be chemically or thermally reduced to form reduced graphene oxide (rGO), which restores much of the sp^2 hexagonal lattice, thereby improving electrical conductivity and enhancing catalytic properties [46]. Reduced graphene oxide-based nanocomposites have been widely investigated for photocatalytic applications because they provide more efficient electron transport pathways compared to GO alone [47].

Metal Oxide Nanoparticles in Photocatalysis

Metal oxide nanoparticles represent an important class of semiconductor materials widely used in photocatalysis, environmental remediation, energy conversion, and sensing applications [48]. These materials possess unique electronic band structures that allow them to absorb photons and generate charge carriers capable of driving redox reactions [49].

When a metal oxide semiconductor absorbs photons with energy equal to or greater than its bandgap energy, electrons in the valence band are excited to the conduction band. This process creates electron–hole pairs within the material. The photogenerated electrons and holes migrate to the surface of the semiconductor, where they participate in oxidation and reduction reactions with adsorbed molecules [50].

Zinc oxide (ZnO) nanoparticles have been extensively studied as photocatalysts owing to their wide bandgap energy of approximately 3.37 eV and high exciton binding energy. These properties enable ZnO to generate reactive radicals capable of degrading organic pollutants under ultraviolet irradiation. Titanium dioxide (TiO_2) is another widely used photocatalyst known for its high stability, strong oxidative potential, and resistance to photocorrosion [51].

Iron oxide (Fe_3O_4) nanoparticles have attracted significant attention owing to their magnetic properties, which allow easy separation of catalysts from treated water using an external magnetic field. These materials are particularly useful in photo-Fenton processes, where iron ions catalyse the formation of hydroxyl radicals for pollutant degradation [52]. Cadmium oxide (CdO) nanoparticles have also been investigated for photocatalytic applications owing to their strong absorption in the visible light region. These materials exhibit high catalytic activity in degrading dye molecules under light irradiation [53].

Despite their advantages, metal oxide nanoparticles have several inherent limitations. The rapid recombination of photogenerated electron–hole pairs is one of the major factors that limit photocatalytic efficiency [54]. In addition, nanoparticles tend to aggregate due to high surface energy, which reduces the available surface area for catalytic reactions. Integrating metal oxide nanoparticles with GO has been shown to significantly improve photocatalytic performance. The GO sheets act as conductive substrates that facilitate charge transfer and suppress electron–hole recombination [55]. As a result, the photocatalytic efficiency of metal oxide nanoparticles is significantly enhanced in graphene-based nanocomposites. Figure 3 illustrates the fundamental electronic process where the absorption of photons with energy equal to or greater than the bandgap triggers the excitation of electrons from the valence band to the conduction band. This creates electron–hole pairs that migrate to the semiconductor surface to initiate redox reactions with adsorbed pollutants. Figure 3 also highlights the specific roles of various oxides, including ZnO (ultraviolet activation and high exciton binding energy), TiO_2 (high stability and oxidative potential), Fe_3O_4 (magnetic recovery and photo-Fenton activity), and CdO (visible light absorption). Finally, the right panel demonstrates how integration with GO overcomes inherent limitations such as rapid charge recombination and nanoparticle aggregation by providing a conductive substrate for efficient electron transport and increased surface area.

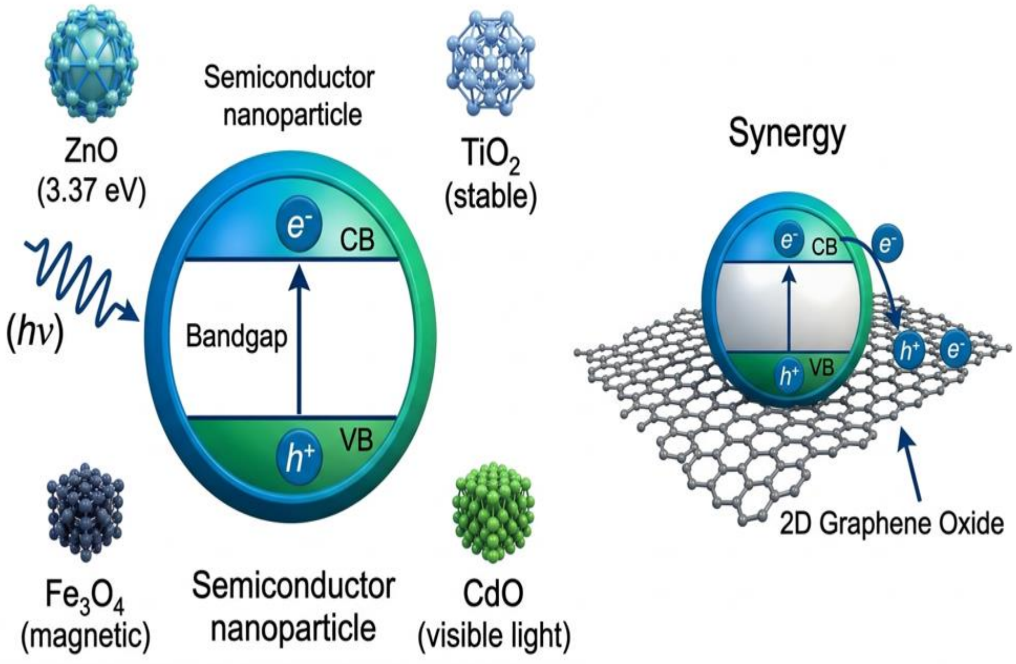

Figure 3: Schematic representation of the photocatalytic mechanism and synergistic properties of metal oxide–graphene oxide nanocomposites

Synthesis of Metal Oxide–Graphene Oxide Nanocomposites

The synthesis of metal oxide nanoparticle-decorated GO nanocomposites is an important step in determining their structural properties and catalytic performance. Several synthesis techniques have been developed to fabricate these hybrid materials with controlled particle size, morphology and distribution [56].

Hydrothermal and solvothermal methods are among the most widely used techniques for synthesising metal oxide–GO nanocomposites. In these methods, metal precursors and GO are dispersed in a solvent and heated in a sealed autoclave at elevated temperature and pressure. The high-temperature conditions promote nucleation and growth of metal oxide nanoparticles directly on the GO surface [57]. This process results in well-dispersed nanoparticles with strong interfacial interactions with the GO matrix.

The sol–gel method is another widely used technique for preparing nanocomposites. In this method, metal alkoxide precursors undergo hydrolysis and condensation reactions to form a metal oxide network within the GO framework [58].The sol–gel process offers excellent control over particle size and morphology, making it suitable for synthesising uniform nanocomposite structures [59].

Green synthesis approaches have also gained increasing attention owing to their environmental friendliness. These methods used plant extracts, microorganisms or biomolecules as reducing and stabilising agents for nanoparticle synthesis. Green synthesis reduces the use of toxic chemicals and minimises environmental impact, making it a promising approach for sustainable nanomaterial production. Another important technique involves the in situ growth of metal oxide nanoparticles on GO sheets [60]. In this approach, metal ions are directly deposited and converted into metal oxide nanoparticles on the GO surface. This method ensures strong bonding between nanoparticles and GO, leading to improved stability and catalytic performance (see Table 1).

Table 1: Summary of graphene oxide-based metal oxide nanocomposite catalysts for photocatalytic degradation of organic dyes

Nanocomposite catalyst	Synthesis method	Target dye	Degradation efficiency, %	Key findings	Reference
ZnO/GO	Solvothermal	Methylene blue	~95	Improved photocatalytic efficiency due to enhanced charge separation	[61]
Fe_3O_4/ZnO/rGO	Hydrothermal	Organic dyes	> 90	Photo-Fenton degradation with high catalytic stability	[62]
GO/ZnO with metal nanoparticles	Chemical reduction	Organic dyes	~92	Enhanced visible-light photocatalytic activity	[63]
CdO/rGO	In situ growth	Methylene blue	~88	Strong UV-driven photocatalytic performance	[64]
Transition metal oxide/GO	Hydrothermal	Textile dyes	> 93	Multifunctional catalytic applications	[65]
Zn nanoparticles/GO	Chemical synthesis	Basic blue dye	~90	High adsorption and degradation capacity	[66]

Environmental and Toxicological Concerns

Despite the promising applications of metal oxide nanoparticle-decorated GO nanocomposites in wastewater treatment, potential environmental and health risks associated with nanomaterials must be carefully considered [67]. Nanoparticles released into aquatic environments may interact with microorganisms, plants and animals, potentially causing oxidative stress and cellular damage [68].

Metal oxide nanoparticles may also accumulate in biological systems and enter the food chain, leading to long-term ecological consequences. It is therefore essential to evaluate the environmental impact and toxicity of nanomaterials before their large-scale application in wastewater treatment systems [69].

Immobilisation of metal oxide nanoparticles on GO matrices provides an effective strategy to reduce nanoparticle mobility and environmental release. These nanocomposites exhibit improved stability, recyclability, and reusability compared to free nanoparticles [70]. In addition, magnetic nanocomposites containing iron oxide can be easily separated from treated water using magnetic fields, reducing the risk of nanoparticle contamination.

Future Perspectives

To realise the full potential of metal oxide-decorated GO nanocomposites, future research must transition from laboratory-scale experiments to robust industrial applications. First, there is a critical need to design advanced architectures, such as Z-scheme or S-scheme heterojunctions, which can maximise visible-light harvesting and further suppress charge carrier recombination beyond current limits. Since ultraviolet light represents only a small fraction of solar radiation, engineering these materials with precisely tuned electronic bandgaps is essential to achieving high solar-to-chemical conversion efficiency. Second, the development of multifunctional nanocomposites capable of simultaneously removing complex mixtures of pollutants, including heavy metals and emerging pharmaceutical contaminants, alongside organic dyes should be researched. Third, integrating photocatalytic materials with advanced adsorption and ceramic membrane technologies (photocatalytic membrane reactors) could further enhance treatment synergy and throughput. Fourth, the large-scale implementation of GO-based photocatalysts demands rigorous investigation into catalyst stability, long-term reusability, and life-cycle economic feasibility. Finally, future studies should prioritise developing magnetic or immobilised catalyst systems to facilitate easy recovery and minimise secondary nano-toxicity in treated effluents. Advances in green synthesis techniques and the integration of machine learning for predicting optimal material compositions will play an important role in making these technologies environmentally and commercially viable [71], [72].

Conclusion

Metal oxide nanoparticle-decorated GO nanocomposites represent a promising class of photocatalytic materials for the degradation of dye pollutants in wastewater. The novelty of these systems lies in the strategic engineering of the interface between the GO framework and semiconductors, which facilitates a dual-functional mechanism: superior organic pollutant sequestration and ultra-fast charge separation. Numerous studies have demonstrated the effectiveness of these nanocomposites in degrading various synthetic dyes under ultraviolet and visible light irradiation. The key takeaway from recent advancements is that the performance of these hybrids can be precisely tuned by controlling the oxygen-containing functional groups on the GO surface. With continued research and technological advancements, GO-based nanocomposites are expected to play an increasingly important role in sustainable wastewater treatment technologies.

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