



Graphene-, GO-, and rGO-supported photocatalysts for degradation of organic pollutants: A comprehensive review

Dibya Ranjan Rout^{a,*}, Hara Mohan Jena^b, Aditya Kumar^{a,*},
Omirserik Baigenzhenov^c, Ahmad Hosseini-Bandegharai^{d,e,f}

^a Department of Chemical Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand 826004, India

^b Department of Chemical Engineering, National Institute of Technology, Rourkela, Orissa 769008, India

^c Department of Metallurgical Engineering, Satbayev University, Almaty, Kazakhstan

^d Faculty of Chemistry, Semnan University, Semnan, Iran

^e Department of Sustainable Engineering, Saveetha School of Engineering, SIMATS, Chennai, Tamil Nadu 602105, India

^f Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab 140417, India

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ABSTRACT

Water scarcity and contamination are critical global concerns, with organic pollutants such as dyes, phenolic compounds, pharmaceuticals, and pesticides increasingly entering aquatic systems and posing serious risks to ecosystems and human health. Among various treatment technologies, photocatalysis has emerged as a sustainable and effective strategy for wastewater purification, particularly for degrading persistent organic contaminants. However, conventional metal-semiconductor photocatalysts suffer from inherent drawbacks, including limited visible-light absorption, sluggish surface kinetics, and rapid electron-hole recombination, which restrict their large-scale applicability. These challenges can be addressed by incorporating graphene and its derivatives graphene oxide (GO) and reduced graphene oxide (rGO) which provide high surface area, excellent electron mobility, and tunable chemical functionality, making them ideal co-catalyst supports. Unlike numerous reviews that broadly summarize graphene-based photocatalysts, the present work adopts a pollutant-specific comparative framework. It systematically evaluates the performance of graphene, GO, and rGO-based composites in degrading four major categories of contaminants: dyes, phenolic compounds, pharmaceuticals, and pesticides. Special emphasis is placed on understanding the role of operational parameters such as pH, oxidizing agents, light wavelength, photocatalyst dosage, and pollutant concentration in influencing degradation outcomes. Mechanistic insights, recyclability, and efficiency trends are critically examined through case studies, highlighting both synergies and limitations across pollutant classes. By adopting this targeted approach, the review not only underscores key advancements but also identifies existing knowledge gaps, offering valuable perspectives for designing next-generation graphene-based photocatalysts tailored to specific water pollutants.

* Corresponding authors.

E-mail addresses: dvrout@gmail.com (D.R. Rout), hmjena@nitrrkl.ac.in (H.M. Jena), aditya@iitism.ac.in (A. Kumar), o.baigenzhenov@satbayev.university (O. Baigenzhenov), ahoseinib@semnan.ac.ir (A. Hosseini-Bandegharai).

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1. Introduction

‘Water’ is the most precious thing amongst all things available on Earth. Any kind of life on earth does not exist without water; it is important to maintain quality of life and earth ecology (Rout and Jena, 2022a). Freshwater makes up just 3 % of all the water on Earth and the rest 97 % is saline (Musie and Gonfa, 2023). The 3 % fresh water is made up of groundwater beneath the earth’s surface and is haphazardly dispersed around the planet’s surface in the form of rivers, ponds, lakes, and many other species (Ahuja, 2021). Only 2.5 % of Earth’s total waters are drinkable freshwaters, with surface waters comprising 1.2 % of the quantity. The residual waters are trapped behind the ice and within the soil. Lakes comprise 20.9 % of surface freshwaters, whilst rivers account for 0.49 % (El-Ghonemy, 2012). Most of the water requirement for human use comes from rivers and lakes, accounting for 60 % of the overall water. In the human body, 82 % of blood, 90 % of the lungs, and 95 % of brain contain water (Ramalingam et al., 2022). Water is an essential element in all cells in human body, so this substance is termed the “building material” (Jéquier and Constant, 2010). Water is employed for numerous applications, including culinary activities, sanitation, agriculture, and production. Water is a vital component of the human body that fulfils essential hydration needs for life (Armstrong and Johnson, 2018).

In recent years, global water shortage has emerged due to insufficient freshwater to satisfy the demands of the present population. The United Nations World Water Development report indicates that over 748 million individuals globally lack access to potable water, and the demand for water in industrial manufacturing is projected to rise by 400 % by 2050 (Musie and Gonfa, 2023). The issue is more severe in underdeveloped nations, with 3.2 million youngsters succumbing annually to inadequate sanitation and hazardous drinking water (Zhou et al., 2018). In the past few decades, uncontrolled urbanization, intensive industrialization, growing population, and unnecessary exploitation of natural water resources have negatively impacted the quality of fresh water, and a large amount of pollutants were released into this freshwater resource (Baig et al., 2019).

Among the major contributors to water contamination are organic pollutants, which include dyes, pesticides, pharmaceuticals, endocrine-disrupting chemicals (EDCs), and phenolic compounds (Si et al., 2022; Chakraborty et al., 2022; Shahryari et al., 2022). Continuing discharging of contaminants from municipal activities, domestic, industrial, and agricultural sources into natural waters



Fig. 1. Various water pollution sources.

deteriorates the quality and quantity of resources of useable water (Liu et al., 2021; Mohan et al., 2014; Grandclément et al., 2017; Chowdhury et al., 2016) and Fig. 1 shows various reasons for water pollution. The wastes generated from agriculture polluted about 70 % of the world's total usable water (du Plessis, 2022). Overdoing pesticides and fertilizers for more production has become the principal source of water pollutions. The excess pesticides and fertilizers that are not used are sprayed on the surface of soil and, after raining, mixes with the lake and river water, polluting it and poisoning the entire water ecosystem (Syafudin et al., 2021). Table 1 shows the various pollutants released by various types of industries. Presence of organic dyes in water causes liver and kidney damage, failure of heart, and teratogenic, carcinogenic, and mutagenic impacts on human cells (Vishnu et al., 2021; Rout and Jena, 2021, 2022a). Organic pollutants in water, including pesticides, EDCs, phenolic pollutants, and insecticides, have a variety of health consequences on both humans and aquatic creatures (Al-Musawi et al., 2022; Bervia Lunardi et al., 2022; Zhu et al., 2022a). The above pollutants in water can cause nephropathy, diarrhea, diabetes, skin anemia, and lung cancer (Zhu et al., 2022b; Santhosh et al., 2017).

Even at trace concentrations, these contaminants alter the physicochemical properties of water, disrupting pH, conductivity, and dissolved oxygen balance. Such alterations not only degrade water quality but also pose serious risks to human health, leading to cancers, organ damage, and reproductive disorders, while simultaneously harming aquatic biodiversity. Currently, several procedures have found exploitation in the removal of pollutants from wastewater, viz. sedimentations, flocculation, and coagulations (Al-Hamadani et al., 2016; Cheng et al., 2021), electrochemical separation (Thamaraiselvan et al., 2021), chemical precipitations (Pohl, 2020), ion exchange methods (Charles et al., 2016), filtration techniques (Thamaraiselvan et al., 2021), sorption technologies (Rout and Jena, 2021, 2022a, 2022a), photocatalysis (Rout et al., 2022), and biological processes (Cherniak et al., 2022; Daud et al., 2022). Nonetheless, numerous treatment systems exhibit drawbacks, such as elevated operational costs, substantial sludge generation, disposal challenges, protracted processes, and technical constraints for industrial exploitations (Rout and Jena, 2022b). Among these photocatalytic degradation, categorized as an advanced oxidation process, has emerged as a highly efficient method for organic pollutant remediation owing to its relatively low operational cost, minimal generation of toxic by-products, superior degradation performance, and capability to mineralize persistent organic pollutants (Rout et al., 2025). Graphene and its derivatives are considered as the most advanced supported materials for the synthesis of photocatalyst among all the carbonaceous materials because of their unique characteristics (Table 2). Graphene and its derivatives have excellent properties such as large delocalized π -electron system, enhanced active sites, high chemical stability, and very high surface area, making them efficient materials for wastewater treatment application (Rout and Jena, 2022b).

Considering the growing challenges of water pollution, the present review begins with an overview of its impact on water resources and a critical evaluation of conventional and emerging wastewater treatment strategies. It then focuses on the potential of graphene-based photocatalysts, examining the synthesis and physicochemical properties of graphene, graphene oxide (GO), and reduced graphene oxide (rGO). Particular attention is given to synthesis methods, the influence of structural and operational parameters on photocatalytic degradation, and their role in improving treatment efficiency. Furthermore, the review highlights the fundamental principles, underlying mechanisms, recent developments, and key outcomes associated with graphene-supported semiconductor catalysts, supported by schematic illustrations for clarity. The growing importance of graphene-derived photocatalysts in addressing water contamination underscores the need for this comprehensive analysis. Despite extensive studies on graphene, GO, and rGO in photocatalytic systems, there remains a lack of focused examination of how these materials function synergistically to enhance the degradation of organic pollutants.

2. Various methods for water treatment

To enhance the quality waters, mitigate health issues and diseases, and provide a conducive habitat for marine creatures, it is imperative to address the treatment of constantly released wastewater from diverse sources. Currently, several procedures have found exploitation in the removal of pollutants from wastewater, viz. sedimentations, flocculation, and coagulations (Al-Hamadani et al., 2016; Cheng et al., 2021), electrochemical separation (Thamaraiselvan et al., 2021), chemical precipitations (Pohl, 2020), ion exchange methods (Charles et al., 2016), filtration techniques (Thamaraiselvan et al., 2021), sorption technologies (Rout and Jena, 2021,

Table 1
Various types of pollutants released by various industries.

Type of Industry	Major Pollutants Released	Specific Examples
Glass industries	Heavy metals	Chromium (Cr), Iron (Fe), Cadmium (Cd), Nickel (Ni)
Chemical fertilizer industries	Nutrients, salts	Ammonia (NH ₃), Potassium (K ⁺), Phosphorus (PO ₄ ³⁻), Urea
Paper industries	Organochlorines, furans, phenolic compounds	Dibenzo-p-dioxin, Benzofuran, Chlorophenols
Leather industries	Heavy metals, dyes, salts, solvents	Chromium salts (Cr ³⁺ , Cr ⁶⁺), Sulfides, Alkalis, Acid dyes (Reactive Black 5), Solvents
Sugar industries	Organic load, biodegradable waste	Alcohol, Molasses, Sucrose, Lignocellulosic residues
Textile industries	Dyes, pigments, surfactants, detergents	Azo dyes (Methyl Orange, Congo Red), Reactive dyes (Reactive Blue 19), Pigments (TiO ₂ , carbon black)
Pharmaceutical industries	Active pharmaceutical ingredients (APIs), antibiotics, hormones	Diclofenac, Ibuprofen, Ciprofloxacin, Sulfamethoxazole, Estradiol
Agrochemical industries	Pesticides, herbicides, insecticides	Atrazine, Malathion, Glyphosate, Endosulfan
Oil refinery/ Petroleum industries	Hydrocarbons, phenolics, polycyclic aromatic hydrocarbons (PAHs)	Benzene, Toluene, Xylene, Naphthalene, Phenol

Table 2
Properties of single layer graphene at room temperature.

Characteristics	Value
Optical transparency	97 %
Bond length of C–C	0.142 nm
Specific surface area (BET surface)	2630 m ² /g
Thermal conductivity	5000 W/m.K
Young modulus	1100 Gpa
Resistivity	10–6 Ω cm
Carrier density	1012 cm ⁻²
Fractural strength	125 GPa
Electron mobility	200,000 cm ² /V.s

2022a, 2022a), photocatalyses (Rout et al., 2022), and biological processes (Cherniak et al., 2022; Daud et al., 2022). Nonetheless, numerous treatment systems exhibit drawbacks, such as elevated operational costs, substantial sludge generation, disposal challenges, protracted processes, and technical constraints for industrial exploitations (Rout and Jena, 2022b).

Conventional wastewater treatment methods, including physical approaches such as adsorption, sedimentation, coagulation, and membrane filtration, as well as chemical and biological treatments, are effective in removing contaminants to some extent. However, these processes often face significant drawbacks when dealing with complex or synthetic pollutants. Physical methods generally require subsequent treatments to prevent secondary pollution and frequent regeneration of the treatment medium (Singh et al., 2023). Chemical oxidation processes such as chlorination (Kumari and Kumar, 2023), ozonation (Lim et al., 2022), electrochemical oxidation (Jiang et al., 2021), Fenton oxidation (Walling et al., 2021), and sonolysis (Madhavan et al., 2019) are capable of degrading organic pollutants but are hindered by high operational costs, formation of hazardous by-products, odor issues, limited compatibility with certain contaminants, and safety concerns. These treatment methods used various chemical reagents such as copper-silver ionization system, chlorine dioxide, peroxone (ozone and H₂O₂), chlorine, hypochlorite, chloroisocyanurate, or Fenton's reagent, KMnO₄, for the complete degradation of pollutants to inorganic ions, H₂O, and CO₂ (Cuerda-Correa et al., 2019). Moreover, the use of chlorine and its derivatives is associated with the generation of carcinogenic disinfection by-products, and certain microorganisms exhibit resistance, necessitating higher dosages (Deborde and von Gunten, 2008). Biological methods, including slow sand filters and biologically active carbon systems, are environmentally friendly but insufficient to cope with recalcitrant or emerging pollutants. These limitations highlight the inadequacy of conventional treatment methods for addressing complex wastewater matrices. Consequently, advanced

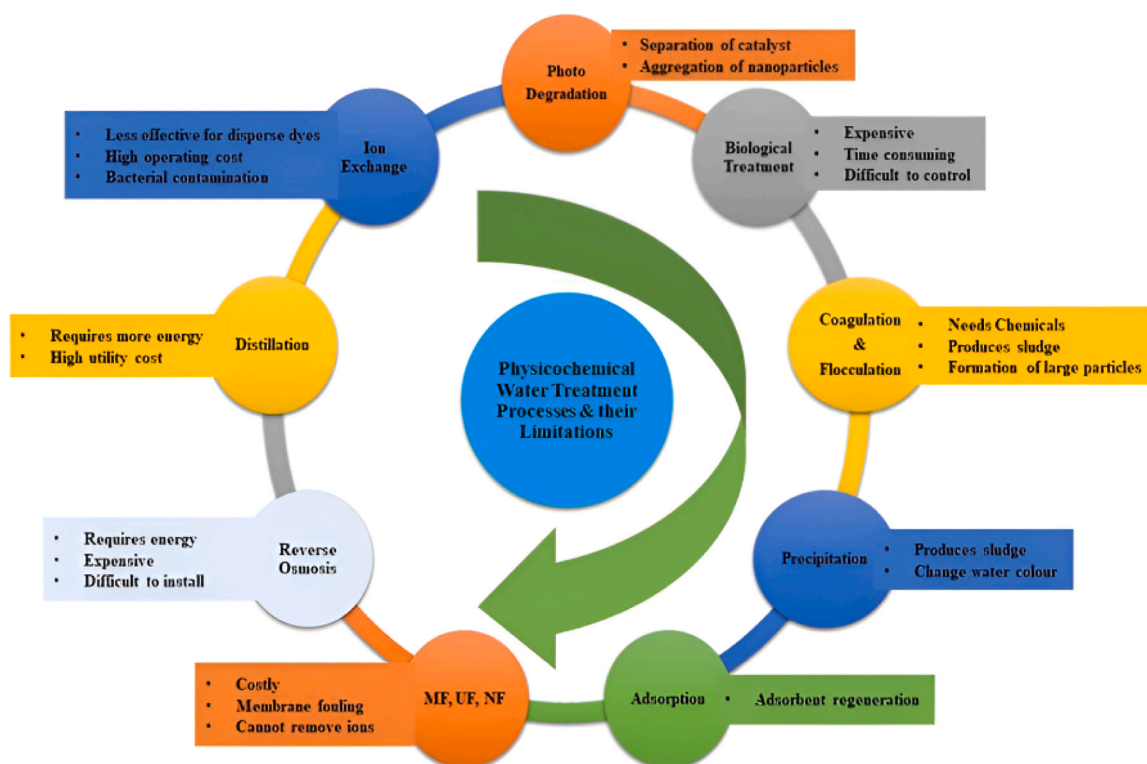


Fig. 2. Conventional water treatment technologies and their disadvantages, Reprinted with permission from (Rout et al., 2023), copyright 2023 Elsevier, License no. 5881891096511.

oxidation processes (AOPs) have gained prominence as promising alternatives, offering the potential for complete mineralization of a wide range of persistent organic contaminants into harmless end products such as CO₂, H₂O, and inorganic ions.

3. Advanced oxidation process (AOPs)

AOPs are potential strategies for mineralizing extremely stable organic contaminants such as pesticides, surfactants, phenolic wastes, coloring chemicals, and some difficult-to-degrade inorganic contaminants (Kumari and Kumar, 2023). Additionally, AOPs are effective for wastewater treatment since they may directly harness solar power for disinfection and chemical cleansing (Cheng et al., 2016). The photocatalytic degradation process is an advantageous alternative and environmentally friendly water treatment approach for decontamination and water disinfection. The technique is of great photochemical stability and efficiently uses solar light and visible light illumination for waters' treatments (Ren et al., 2021). By converting dangerous molecules into non-toxic forms or destroying them entirely, the photocatalytic remediation method removes organic pollutants from polluted water without leaving any harmful byproducts behind.

In photocatalytic reaction, the most important and core of the technology is 'photocatalyst' which composed of two parts i.e. photo means light, which will be used for photon energy source and catalyst which is used to enhance the speed of a chemical reactions by reducing the activation energy (E_a) (Mohamadpour and Amani, 2024). For photocatalysis to occur, the energy of the photons must be more than or equal to the band gap energy, which is the difference between the photocatalyst's VB (valence band) and CB (conduction band) (San Martín et al., 2020). When light falls on the metal semiconductor it emits an electron (e^-)/hole (h^+) pairs and then, because of band gap energy difference, the e^- transfers from the VB to the CB (Cerrato and Paganini, 2020). The h^+ present in the VB of the metal-semiconductor then either degrade water to produce hydroxyl radical ($OH^\bullet$) or oxidize the pollutant to form nontoxic product whereas excited e^- present on CB reduces the dissolved oxygen (O_2) to form superoxide radical ($\bullet O_2^-$) (Pavel et al., 2023). The contaminant or pollutant's organic groups are attacked by the $OH^\bullet$ and $\bullet O_2^-$ free radicals, which then undergo a series of reactions that either render the organic pollutants harmless or cause them to breakdown entirely into CO₂ and H₂O (Lu et al., 2024). While photogenerated e^- and h^+ couples do have a photocatalytic efficiency, they recombine quite easily (Zhou et al., 2024). For this reason, it is important to regulate or reduce the recombination of photogenerated charge carriers in order to augment the photocatalytic activities. The ideal properties which should a photocatalyst requires are inexpensive applicability, cheapness, high surface area, easiness in handling, good crystallinity, non-toxicity, etc., and must not create harmful by-products (Pavel et al., 2023). Fig. 3 illustrates the photocatalytic mechanism, and the Eqs. provide the basic photocatalytic processes.

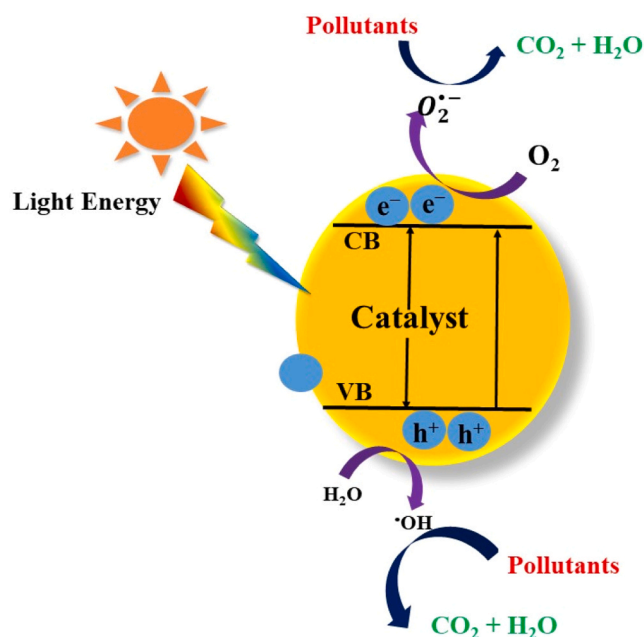
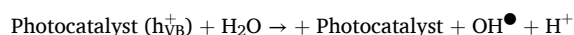
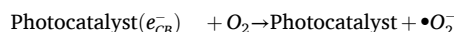
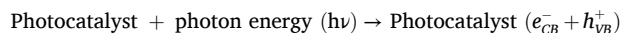
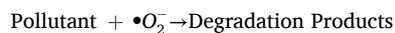
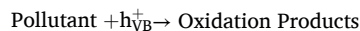
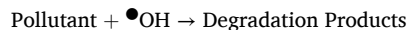
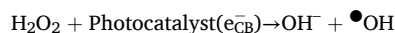
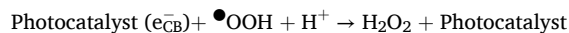
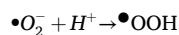


Fig. 3. General photocatalytic mechanism.



Yet, a greater part of photocatalysts experience various disadvantages and have restricted their photocatalytic execution. Many metals and metal oxides, including Mn_2O_3 , MoS_2 , BiOBr , TiO_2 , ZnO , CdS , etc., are highly regarded as photocatalysts, owing to their remarkable photocatalytic activity and suitable band gaps. However, these materials also have some bottlenecks such as having a fast recombination rate of e^-/h^+ pair, insufficient response to visible light, and insufficient contact with pollutant molecules (Kusmierek, 2020). To improve these drawbacks, in recent years the metal semiconductors are combined with graphene and its derivatives to form a highly effective photocatalyst that efficiently degrade pollutants (Zhang et al., 2023). Graphene and its derivatives are considered highly advanced materials for enhancing the photocatalytic performance of semiconductors due to their outstanding properties, which are summarized in Table 2. The efficient use of graphene and its derivatives in wastewater treatment is due to their remarkable features, including a huge delocalized π -electron systems, improved active locales, great chemical stabilities, and a large surface areas (Assafi et al., 2025; Jiang et al., 2025).

Graphene and graphene-based composites stand out as attractive options for photocatalysis compared to other nanocomposites and conventional AOPs due to their unique physicochemical properties. Graphene offers an exceptionally large surface area, high electron mobility, and excellent adsorption capacity, which enhance light absorption and charge carrier separation, thereby improving photocatalytic efficiency (Rout et al., 2025). When combined with semiconductors or metals, graphene derivatives such as GO and rGO act as electron acceptors and transporters, minimizing recombination losses. Unlike traditional AOPs that often require harsh conditions, costly reagents, or generate secondary pollution, graphene-supported photocatalysis is more sustainable, efficient under mild conditions, and suitable for large-scale water purification. These advantages make graphene composites highly promising for environmental remediation applications.

4. Graphene and its properties

Graphene, a sheet of carbon with only one layer, was created in 2004 by Geim and Novoselov. The carbon atoms in graphene sheets are organized in a flat 2D (two-dimensional) layers in honeycomb-like lattice structures (Geim and Novoselov, 2007). The carbon family can be completed by rolling it into 1D carbon nanotubes, stacking it into 3D graphite, and wrapping it into 0D fullerene, all in terms of dimensions (Fig. 4) (Zhao et al., 2020). In contrast to other nanosystems, the graphene's delocalized π -electrons offer stability. Graphene is an exceptional material, characterized by an electron mobility of $200,000 \text{ cm}^2/\text{V}\cdot\text{s}$, an optical transparency of

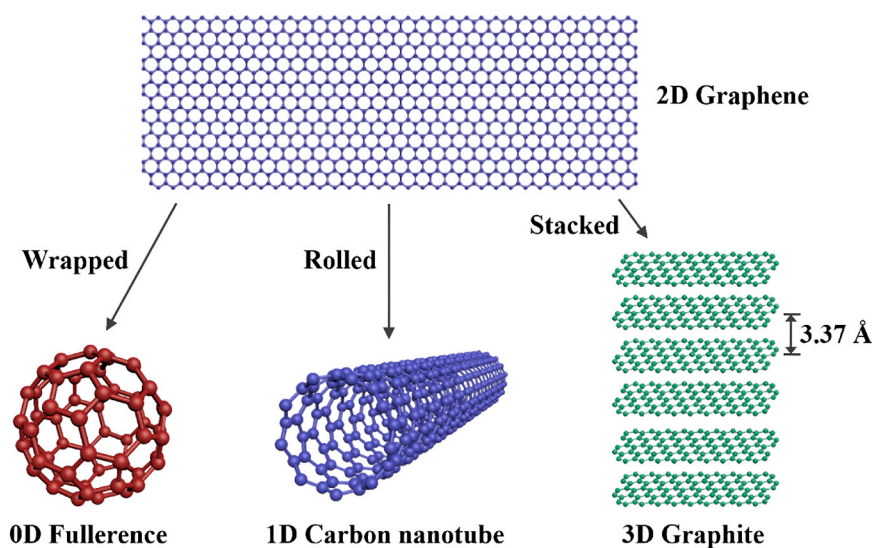


Fig. 4. Graphene, the mother of all graphitic forms from 2D graphene to 0D fullerene, 1D carbon nanotube, and 3D graphite, Reprinted with permission from (Zhao et al., 2020), copyright 2020 Elsevier, License no. 5882911199229.

approximately 97.3 %, and an impressive thermal conductivity of 3000 W/m·K (Ranjan Rout and Mohan Jena, 2022; Khaliq et al., 2025). Graphene, with a thickness of only 0.335 nm, is the most ultra-thin substance that has ever been created (Singh et al., 2025). Graphene stands out due to its exceptionally high surface area, measuring around 2630 m²/g and this value surpasses that of carbon nanotubes (1315 m²/g) and graphite (~10 m²/g) (Sahu et al., 2021). Current applications of graphene in engineering include aerospace, sound sensors, biomedical devices, organic light-emitting diodes, energy storage devices, biosensors, protection coatings, integrated circuits, and wastewaters treatments among others (Bai et al., 2025; Zia et al., 2025). Because of graphene's usefulness, scientists throughout the world are investigating its applications as well as those of related materials, such as GO and rGO.

The potential environmental benefits of compounds based upon graphene, like the ability to adsorb and photodegrade contaminants in water, have picked the curiosity of scientists all around the globe. The adaptability of graphene and its derivatives to degrade an ample range of organic contaminants has driven this growing interest. As photocatalysts, GO and rGO have been found to have extensive usage in the degradation of organic pollutants from waters. The characteristics of pure graphene are similar to those of GO and rGO, however they differ slightly. Graphene in its purest form lacks any functional groups, while GO and rGO have all sorts of them attached to their surfaces and edges, including carboxyl (-COOH), hydroxyl (-OH), and carbonyl (-C=O) (Rout and Jena, 2022a). Both rGO and GO are functional groups that can degrade organic contaminants, which makes them a good candidate for this task. Interactions with other aromatic contaminants can occur through electrostatic and π - π interactions due to the cyclic aromaticity seen in GO and rGO. Graphene, the "God gifted two-dimensional (2D) material," provides an exceptional platform for semiconducting photocatalyst materials due to its ample surface area, brilliant electrical conductivity, and flat surface area (Khan, 2024).

5. The necessity of this review

Composite photocatalysts based on graphene, GO, and rGO have been studied for the effective removal of organic contaminants from wastewaters, including chemicals that disturb endocrine systems (Wang et al., 2014), phenols (Kim et al., 2019), chlorophenols (Sharma and Lee, 2016), pesticides (Zhu et al., 2020), dyes (Rout et al., 2022), and emerging pollutants (Olatunde and Onwudiwe, 2021). The literature that is now available frequently concentrates on discrete topics like synthesis techniques, energy storage uses, or particular pollutant degradation mechanisms (Table 3). This all-encompassing strategy will give scientists and industry professionals a strong basis for developing graphene-supported photocatalysis for the degradation of organic contaminants. Fig. 5(a) demonstrate the number of scientific publications published related to various organic pollutant degradation using graphene-, rGO-, and GO-based photocatalyst with the keywords "Graphene" and "Photocatalysis" for the previous 10 years. The use of graphene-based photocatalysts for the degradation of various pollutants is increasing rapidly, as seen in Fig. 5(a). Consequently, as can be grasped from Fig. 5 (b), the number of review publications covering this topic is rising annually. A lot of research on using graphene and graphene-based materials to purge and disinfect water has been completed. Given the aforementioned, this review article compiles the relevant research on graphene and its derivatives as a photocatalyst for the organic pollutant degradation that has previously been published.

6. Synthesis techniques and properties of graphene-supported materials

The crystal structural form of graphene is shown in Fig. 6a. It can be seen that a honeycomb-like structure are formed between the carbon atoms and this is visible due to the presence of π and σ -bonds. The various synthesis routes which are currently available for graphene synthesis are chemical vapor decomposition (CVD) (Zhang et al., 2013), chemical reduction of exfoliated graphene oxide (Stankovich et al., 2007), bottom-up synthesis from organic molecules (Mbayachi et al., 2021), liquid phase utilization (Ghanbari et al., 2019), carbon nanotube unzipping (Mondal et al., 2018), and epitaxial growth of SiC (Yazdi et al., 2016). The benefits and bottlenecks of the several graphene production processes are detailed in Table 4. Although it has its limits, chemical reduction of GO stands out among these strategies for preparing large amounts of graphene. Graphene synthesis nearly always results in compounds and dispersions that are not monodisperse, and mass-producing single-layer graphene is an extremely expensive ordeal.

Epitaxial growth of graphene involves thermal decomposition of silicon carbide (SiC) at high temperatures, where silicon atoms sublime leaving behind graphitized carbon layers (Idczak et al., 2025). This method yields wafer-scale, high-quality graphene directly on insulating substrates, suitable for electronic applications. Micromechanical exfoliation, also known as the "Scotch tape method," involves repeatedly peeling layers from bulk graphite using adhesive tape to obtain single or few-layer graphene (Goodrum et al., 2024). This technique produces high-quality defect-free graphene, though with very low yield and scalability. CVD synthesizes graphene by decomposing hydrocarbon gases (e.g., methane) on metal substrates like copper or nickel at high temperatures (Nam et al., 2024). It enables large-area, uniform, and high-quality graphene films suitable for industrial applications. The colloidal suspension method produces graphene by liquid-phase exfoliation of graphite in suitable solvents or with surfactants, yielding stable graphene dispersions (Sellathurai et al., 2023). This approach is cost-effective, scalable, and ideal for solution-processed applications like coatings and inks. The unzipping of carbon nanotubes (CNTs) method involves oxidative, plasma, or chemical treatments that longitudinally cut CNTs into graphene nanoribbons (Yang et al., 2016). This technique yields narrow, edge-functionalized graphene structures with unique electronic and chemical properties. The GO reduction method synthesizes graphene by chemically, thermally, or electrochemically reducing graphene oxide to remove oxygen-containing groups. It is a scalable and low-cost approach, though the resulting graphene often contains residual defects.

Oxidized GO is a reactive species because of numerous oxygenated functional groups on its surface (Fig. 6b) (Rout and Jena, 2023). In addition, GO is a type of monolayer graphite oxide that can be created by exfoliating multilayer graphite oxide using methods such as mechanical stirring, rapid heating, sonication, arc discharge, or microwaves (Zhao et al., 2015). While there are a number of viable options for GO synthesis, the most effective one is the Improved Hummer's approach. The Improved Hummer's approach is a

Table 3

Some reviews which have previously been published regarding the use of graphene-supported photocatalysts for decomposition of organic contaminants.

Titles	Summaries	Bridged gaps in the current work	Ref.
An evaluation of the improved catalytic performance of rGO/GO-hybrid-nanomaterials in photocatalytic degradation and antibacterial activity processes for wastewater treatment: A review	The review reports the enhancement of photocatalytic degradation and antibacterial activity of rGO/GO composites through synergistic redox reactions, focusing on flexible production methods enabling applications in heterogeneous catalysis. The review also focuses on improving performance and addressing existing limitations.	A more comprehensive analysis is needed to explore characteristics, synthesis processes, and degradation mechanisms of graphene-supported photocatalysts in wastewater treatment, along with a look at long-term viability, cost-effectiveness, and sustainability.	(Abuzeyad et al., 2023)
Graphene-based materials for metronidazole degradation: A comprehensive review	Focuses specifically on the use of graphene-based materials for the adsorption and photocatalytic degradation of metronidazole (MNZ), analyzing influencing parameters and basic mechanisms.	A broader perspective is needed to be offered by examining general organic pollutants, thus widening the applicability of the findings in studies related to graphene-supported photocatalysts.	(Vasseghian et al., 2022a)
Remediation of pharmaceutical pollutants using graphene-based materials - A review on operating conditions, mechanism and toxicology	Reviews the use of graphene-based materials for removing ibuprofen and ciprofloxacin from water via adsorption, photocatalysis, and electro-Fenton processes, focusing on operating conditions and mechanisms.	There is a need for critical evaluation of graphene, GO, and rGO-based photocatalysts for organic pollutant degradation, detailing parameters (pH, light, etc.), mechanisms, recyclability, and case studies.	(Akash et al., 2022)
Graphene-based photocatalysts for degradation of organic pollution	Concentrates on the synergistic effects of graphene with various semiconductors in photocatalytic degradation, providing an overview of synthesis, characterization, and performance.	Comprehensive evaluation of graphene, GO, and rGO-based photocatalysts for organic pollutant degradation is scientifically necessary for researchers.	(Zhang et al., 2023)
Graphene-based nanocomposites and nanohybrids for the abatement of agro-industrial pollutants in aqueous environments	Reviews graphene-based nanocomposites for agro-industrial pollutant removal, highlighting their physicochemical properties and functionalization methods graphene. It emphasizes graphene's potential in environmental remediation but lacks details on degradation mechanisms, sustainability, and cost-effectiveness.	Lacks comprehensive analysis of photocatalytic mechanisms, real-world application challenges, graphene's synergistic effects, long-term viability, economic considerations in wastewater treatment, etc.	(Farhan et al., 2022)
Application of graphene-based materials for removal of tetracyclines using adsorption and photocatalytic-degradation: A review	Focuses specifically on the application of graphene-based materials for the removal of tetracyclines from aqueous media by adsorption and photocatalytic degradation.	Providing a broader analysis of graphene-based photocatalysis, considering multiple organic pollutants beyond tetracyclines and addressing the role of different components and parameters is necessary.	(Minale et al., 2020)
Graphene composites in photocatalytic oxidation of aqueous organic contaminants – A state of art	Discusses the fundamental characteristics of graphene composites for photocatalytic enhancement, preparation methods, applications in treating organic compounds, and speculated mechanisms. Also, it examines graphene derivatives' crystal and electronic properties and their role as photocatalytic materials.	A more detailed analysis of degradation parameters (pH, light wavelength), catalyst mechanisms, recyclability, and an up-to-date comprehensive view of graphene-supported photocatalysts in wastewater treatment is necessary.	(Karim and Selvaraj, 2021)
Spotlighting graphene-based catalysts for the mitigation of environmentally hazardous pollutants to cleaner production: A review	The article highlights the benefits of graphene-based catalysts for organic pollutant degradation, discusses challenges in synthesizing graphene and its derivatives, and mentions various performance parameters.	A comprehensive analysis of the interactions among graphene, GO, rGO, and other components, emphasizing their combined impact on pollutant degradation mechanisms. A discussion of eco-friendly production methods of graphene-based materials, ensuring a focus on sustainability in wastewater treatment applications. Analyzing key factors affecting photocatalytic performance.	(Vasseghian et al., 2022b)
Recent developments of two-dimensional graphene-based composites in visible-light photocatalysis for eliminating persistent organic pollutants from wastewater	Mentions the promise of two-dimensional graphene composites for photocatalysis and removing persistent organic pollutants. Discusses challenges like carrier recombination and factors influencing photocatalytic efficiency in wastewater treatment to some extent.	Detailed examination of the synergistic effects of graphene-supported photocatalysts on the degradation mechanisms of various organic contaminants, discussing challenges, as well as in-depth analysis of critical variables affecting photocatalytic performance.	(Zhang et al., 2020)
Carbon nitride- and graphene-based materials for the photocatalytic degradation of emerging water pollutants	Highlights recent developments in carbon nitride- and graphene-based photocatalysts, focusing on GCN activity enhancement and graphene's role as a support.	Analysis of the interactions among graphene, GO, rGO, and other components, emphasizing their combined impact on pollutant degradation mechanisms. A	(Budiarso et al., 2024)

(continued on next page)

Table 3 (continued)

Titles	Summaries	Bridged gaps in the current work	Ref.
Recent advances and prospects on the r-GO incorporated metal oxide semiconductors for enhanced photo-adsorptive abatement of toxic wastewater pollutants	Summarizes the properties and green synthesis of r-GO based materials for organic wastewater pollutant removal, focusing on r-GO composites with metal oxides.	discussion of eco-friendly production methods of graphene-based materials, ensuring a focus on sustainability in wastewater treatment applications. Analyzing key factors affecting photocatalytic performance. A broad review of graphene-supported photocatalysts, including characteristics, synthesis, degradation mechanisms, and real-world applications in wastewater treatment.	(Shukla et al., 2025)
Graphene-based TiO ₂ composites for photocatalysis & environmental remediation: synthesis and progress	The article discusses graphene-based TiO ₂ composites for photocatalysis, focusing on their synthesis and applications in wastewater treatment for removal of some dyes.	Instead of analysis of narrow group of related photocatalysts, providing a comprehensive analysis of graphene-supported photocatalysts is necessary.	(Purabgola et al., 2022)

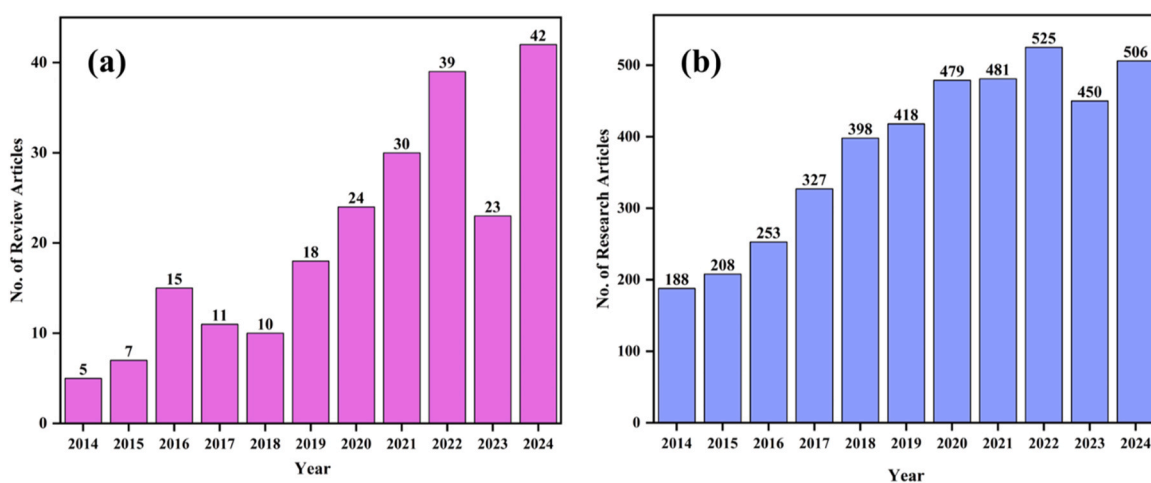


Fig. 5. Number of (a) Review articles and (b) Research articles published from year 2014 – 2024 for photocatalytic degradation of organic contaminants by using keywords graphene-, GO-, and rGO-based photocatalyst acquired from Scopus database.

cost-effective technique relative to the synthesis of monolayer graphene. This process involves in an acidic solution. The graphite powder is chemically oxidized, giving rise to the fabrication of various functional moieties such as --COOH at the ends, while --C=O and --OH moieties are produced in the basal planes (Rout et al., 2019; Rout and Jena, 2022c). Due to these functional groups, GO exhibits inherent hydrophilicity, making it appropriate for waters treatment applications. Due to the existence of several functional groups on graphene oxide layer surfaces, the depth of single-layer graphene oxide ranges from 0.7 to 1.2 nm, which is more than original graphene (0.335 nm) (Rout et al., 2023). Graphene oxide can be described as an extraordinarily generous support, resembling a pliable membrane, anisotropic, colloid, 2-D polymer, liquid crystal, and even amphiphilic solid (Padmajan Sasikala et al., 2018). The functional groups on GO enable its functionalization with various materials for diverse applications.

Reduced graphene oxide (rGO), the reduced form of graphene oxide (GO), is produced through the chemical reduction of GO, or through hydrothermal and thermal hardening techniques (Fig. 6c). The reduction of some oxygenated functional groups in rGO allows for its repeated modification through physical sorption of small molecules and polymeric materials through π - π stacking or non-covalent van der Waals force (Dreyer et al., 2010). Because of this, rGO and the related composite materials have gained a lot of attention and are being considered for a number of potential uses, one of which being water purification. The biocompatibility and distinctive characteristics of graphene have made it an attractive candidate for use as a nanocomposites' support material. 2-D graphene (Fig. 6a) has higher surface area than other materials which contains carbon, fullerenes, carbon nanotubes, and activated carbon. In addition to preventing the aggregation of metal oxides adsorbed on its surface, the increased surface area promotes interfacial interaction with other inorganic/organic equivalents (Zhu and Xu, 2016). Nanocomposites made of immobilized nanomaterials, like metal oxides, can reduce graphene aggregation by acting as spacers between graphene nanosheets. Nanocomposites made of graphene have numerous desirable qualities, such as biocompatibility, an easy way to functionalize them chemically, and good water dispersion (Li et al., 2021).

Due to its sensitivity to oxidative environments, graphene's use as a catalyst on its own is problematic, since its bandgap value is 0 eV (Nandee et al., 2022). As a result, various systems that incorporate modified-metal oxide/graphene or metal oxide/graphene

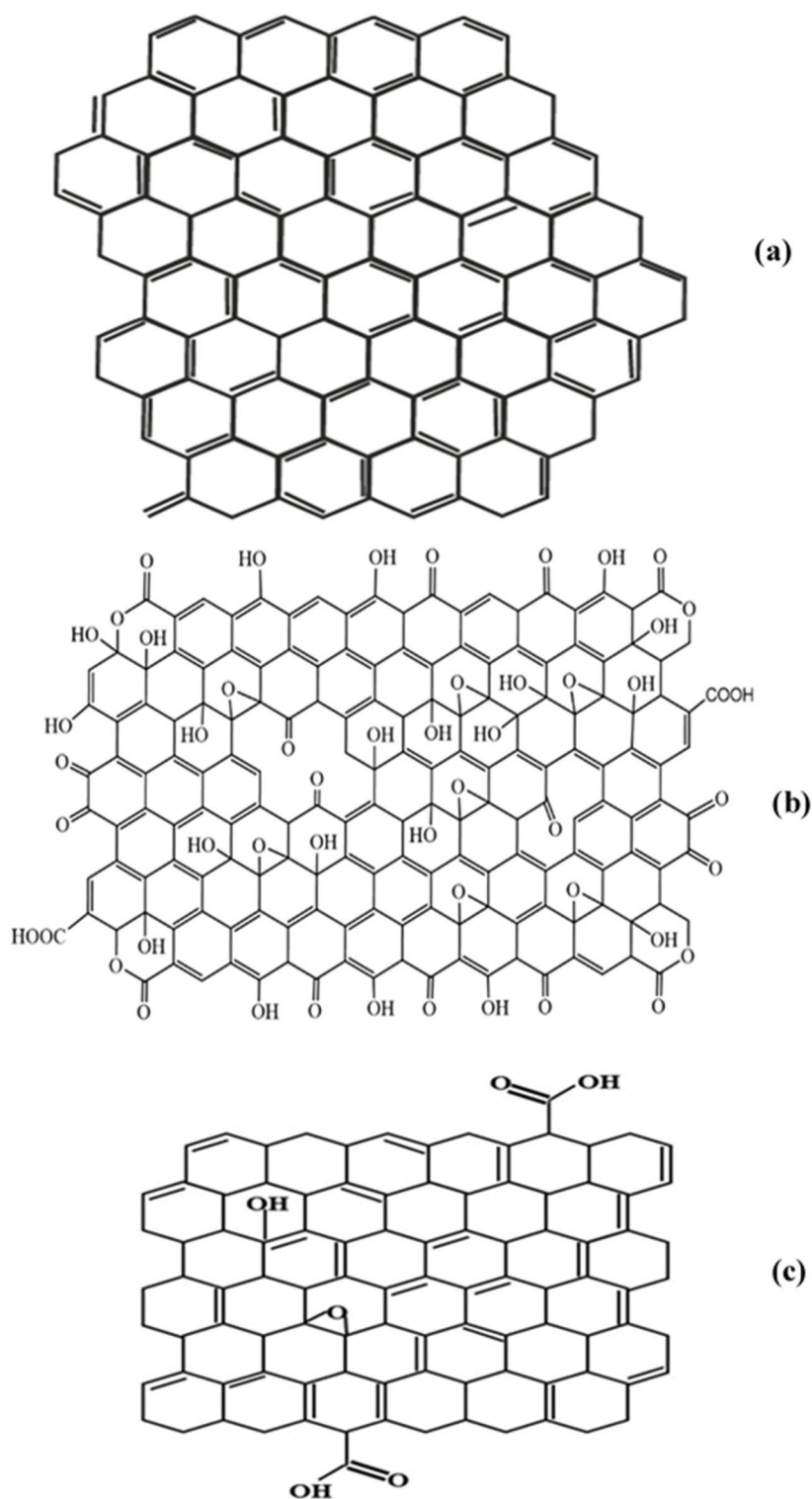


Fig. 6. Crystal structures of (a) Graphene, (b) Graphene oxide, and (c) reduced Graphene oxide.

composites have been investigated for applications involving processes like nanoelectronics, conversion of CO_2 into non-toxic products, storage of hydrogen, wastewater remediation, water splitting for green H_2 generation, indoor air purification, sensors, and supercapacitors, and self-cleaning surfaces. The foundation of these applications primarily stems from their extended absorption of

Table 4

Benefits and drawbacks of various synthesis methods of graphene.

Synthesis method	Advantage	Limitation
Epitaxial growth	• High quality of graphene • Few defects.	• Economically not viable • More temperature required
Micro mechanical exfoliation	• Less defects • Easy process • For fundamental research it is better suited • Excellent quality of graphene	• Mass production is not feasible • Poor reproducibility
CVD	• High quality graphene. • Limited number of defects. • Mass production. • Large area.	• Poor scalability. • Expensive.
Colloidal suspension	• Scalable • High volume of production	• Substantial number of defects.
Unzipping of CNTs	• Appropriate for chemical functionalization. • Scalable with controlled width and edge structures.	• More expensive • Less production
GO reduction	• Mass production. • Economical and facile technique.	• Substantial number of defective locales

light photons, increased stability, enhanced electron-hole separation and migration, and concurrently improved adsorption capacity (Etacheri et al., 2015). Recently, graphene-based photocatalyst has emerged as a viable, environmentally suitable, and cost-efficient technology for waters purification, with numerous visible-light photocatalysts fabricated and evaluated for waters decontamination (Sun and O'Connell, 2022). Research has confirmed that using graphene as a substrate for anchoring catalytic nanoparticles (NPs) creates new opportunities for developing a novel generation of catalysts (García-Zaragoza et al., 2023). Composites made of graphene and semiconductors or metal nanoparticles have opened up new avenues for use in water purification. Research over the last several decades has shown that heterogeneous photocatalysis is crucial to achieving very high photocatalytic efficiencies. However, as previously stated, many photocatalysts have limitations that limit their practical application, such as high band gap, high aggregation, low quantum yield, inefficient solar light harvesting, low stability, etc. One easy way to improve graphene's photocatalytic activity and stabilities is to mix it with nanoparticles and metal oxide semiconductors.

7. Degradation of pollutants using graphene based photocatalyst

7.1. Photocatalytic degradation of dyes

Water pollution resulting from dye contamination is a crucial concern in contemporary society. Organic dyes are discharged into aquatic systems through industrial effluents, agricultural runoff, and chemical mishaps (Kolya and Kang, 2024). Numerous processing units in the pulp and paper, pharmaceutical, plastic, leather, textile, culinary, and paint industries utilize significant quantities of dye and release dye effluents into environmental environments (Rout et al., 2023). The dyeing process necessitates substantial water usage, which is continuously discharged into the environment. The acute toxicity, stability, and environmental persistence over extended periods have raised significant concerns among societies and regulatory bodies worldwide. The presence of dyes in aquatic environments obstructs light penetration, hence diminishing the photosynthetic activity of aquatic flora and lowering dissolved oxygen concentrations in the water (Rout and Jena, 2022a). The effluent containing harmful and carcinogenic colours produced by dyeing companies is poisonous to fish, aquatic microbes, and animals, posing significant hazards to aquatic plants' photosynthesis and thus leading to the degradation of the aquatic ecosystem (Rout and Jena, 2022d). Dye effluents from the photographic and textile industries pose a significant environmental challenge due to their toxicity, undesirable colouration, resistance to chemical, biological, and photochemical degradation and elevated chemical oxygen demand (Rout and Jena, 2021). Dyes can induce allergic reactions, including contact dermatitis, respiratory ailments, irritation of the eyes and respiratory tract, and may even contribute to cancer in the kidneys, urinary bladder, and liver (Rout et al., 2022). Consequently, rapid, efficient, and economical technologies are necessary to eradicate the dyes prior to their discharge into water bodies. The primary environmental impacts of dyes include the mortality of soil microorganisms and the discoloration of aquatic ecosystems; therefore, the removal of dyes from industrial effluent is critically important.

To process these environmentally toxic effluents, a variety of treatment technologies have been employed including coagulation-flocculation (Ibrahim et al., 2024), membrane separation (Yang et al., 2024), solvent extraction (Adedokun et al., 2018), and reverse osmosis (Gubari et al., 2023). The remediation of environmental pollutants in wastewater by active semiconductor photocatalysts has garnered significant interest due to their capacity to entirely decompose organic toxins into CO₂, H₂O, and minerals. Semiconductor-based photocatalysis is the most promising technique, owing to the potential uses, particularly in the degradation of organic pollutants (Wu et al., 2023). Various influential parameters, like catalyst dosage, solution pH, initial concentration of pollutants, the intensity of irradiation light, irradiation time, influence of coexisting ions, and oxidizing species are optimized. The experimental kinetic results of the photocatalytic degradation process are fitted with several kinetic models such as pseudo-first order reactions (De Mello Peters et al., 2018; Sarwar et al., 2023), Langmuir–Hinshelwood first-order kinetics (Rout et al., 2022), and the pseudo-second-order kinetics. More and more, graphene, GO, rGO, and composites of these materials with metals and oxides are being

used as photocatalysts to degrade pollutants. Composite substances based upon graphene have emerged as the gold standard in wastewater treatment, owing to the offered distinct properties, which include extremely mobile charge carriers, a wide variety of functional groups, a large specific surface area, a low recombination rate, and a low band gap (Cheng et al., 2022). The present section delineates the publications of several researchers about the photocatalytic degradation of dyes with graphene-based catalysts.

Table 5 delineates the experimental circumstances, pollutants, and degradation efficiencies of several graphene- and its derivatives-based composites utilized as photocatalysts for the dye decomposition. In their study, Rout et al., (2022) investigated the use of a ternary composite of graphene oxide, zinc oxide, and manganese oxide (GO-ZnO/Mn₂O₃) to decompose malachite green (MG) dye when exposed to solar light (Rout et al., 2022). The photocatalyst showed tremendous degradation capability owing to its low bandgap energy of 1.6 eV and large specific surface area of 75.35 m²/g. Due to its high surface area, it can adsorb more amount of MG dye on its surface which was later degraded by the GO-ZnO/Mn₂O₃ catalyst. Also, the low band gap energy facilitates the easy transfer of e⁻ from the VB to CB so that it can degrades the MG dye. The optimized parameter conditions were pH 8, irradiation time 30 min, catalyst dose 0.2 g/L, and initial MG dye level 50 mg/L. Synthesized GO-ZnO/Mn₂O₃ composites are compared to GO, Mn₂O₃, and GO-ZnO composites in terms of their photocatalytic degradation performance for MG dye. While pure GO-ZnO, GO, and Mn₂O₃, decay 65.85 %, 25.9 %, and 20.2 % of MG dye, respectively, after 30 min under solarlight irradiation, the GO-ZnO/Mn₂O₃ composite degrades 98.75 % of the dye. In addition, a study on MG dye's recyclability found that its degradation efficiency drops slightly (11.65 % reduction) after five cycles. Fig. 7 shows the schematic diagram of MG dye degradation mechanism using GO-ZnO/Mn₂O₃ composite. An extremely effective photocatalyst for the breakdown of MB (Methylene blue) and RhB (Rhodamine B) was synthesized by Hong et al. (2020) using a SnO₂/rGO-HM (hydrophilic macroporous SnO₂/reduced graphene oxide) composite (Hong et al., 2020). The results demonstrated that compared to ordinary SnO₂/rGO, commercial TiO₂, and pure SnO₂ photocatalyst, SnO₂/rGO-HM photocatalyst exhibited superior degradation efficiencies. The optimized parameter conditions were initial level 10 mg/L, catalyst dosage 0.5 g/L, irradiation duration 40 min for RhB dye and 20 min for MB dye and more than 95 % degradation occurs. The monotonous distribution of SnO₂ NPs onto rGO layers, along with the high specific surface area and hydrophilicity nature of the SnO₂/rGO-HM composite, is responsible for the remarkable photo degradation

A ternary hybrid nanocomposite CeO₂/Fe₂O₃/r-GO was synthesized and demonstrated by Gomathi et al. (2023) to be an effective photocatalyst for MB and methyl orange (MO) dye degradation (Gomathi et al., 2023). Interestingly, when exposed to UV light, the hybrid CeO₂/Fe₂O₃/r-GO composite resulted in a 90 % and 86 % reduction of MB and MO dyes, respectively. The activity and crystalline properties of the CeO₂/Fe₂O₃/r-GO composite remained unchanged over five photodegradation phases, which was a tremendous boon for its recycling. The optimized parameter conditions were catalyst dosage 0.1 g/L, initial level 10 mg/L, pH 7 and

Table 5

Photocatalytic decomposition of various dyes using graphene-based photocatalyst materials.

Dye	Catalyst	Energy Source	Operating Conditions	Photocatalytic Degradation (%)	References
Brilliant green (BG)	NiO-CuO-rGO	UV-Visible light	[BG]o = 10 mg/L, pH = t = 60 min, Catalyst dosage = 0.5 g/L	99 %	(Sree et al., 2020)
RhB	Nb ₂ O ₅ -g-C ₃ N ₄ /rGA	Visible	[RhB]o = 20 mg/L, pH = , t = 100 min, Catalyst dosage = 0.3 g/L	94.8 %	(Xu et al., 2020)
MB	NdMnO ₃ :rGO	UV light	[MB]o = 5 mg/L, pH = 8, t = 105 min, Catalyst dosage = 0.05 g/L	55.6 %	(Misra et al., 2023)
MG	rGO/CuS	Sun light	[MG]o = 10 mg/L, pH = 5, t = 90 min, Catalyst dosage = 1 g/L	99.2 %	(El-Hout et al., 2020)
MB	rGO-TiO ₂ /SA/PAM	Mercury lamp	[MB]o = 20 mg/L, pH = 7, t = 100 min, Catalyst dosage = 2 g/L	100 %	(Sawut et al., 2023)
MG	GO-ZnO/Mn ₂ O ₃	Sun light	[MG]o = 50 mg/L, pH = 8, t = 30 min, Catalyst dosage = 0.2 g/L	98.75	(Rout et al., 2022)
MB RhB	SnO ₂ /rGO-HM	Visible light	[MB]o = [RhB]o = 10 mg/L, pH = 8, t = 40 min for RhB and 20 min for MB dye, Catalyst dosage = 0.5 g/L	> 95 % for both MB and RhB dye	(Hong et al., 2020)
MG	S-TiO ₂ /rGO	UV light	[MG]o = 20 mg/L, pH = 7, t = 90 min, Catalyst dosage = 0.4 g/L	99.87 %	(Giang et al., 2022)
MB MO	CeO ₂ /Fe ₂ O ₃ /r-GO	UV light	[MO]o = [MB]o = 10 mg/L, pH = 7, t = 100 min, Catalyst dosage = 0.1 g/L	MB = 90 % MO = 86 %	(Gomathi et al., 2023)
MG	Bi@TiO ₂ -rGO	Visible light	[MG]o = 40 mg/L, pH = 8.3, t = 150 min, Catalyst dosage = 0.05 g/L	93.34 %	(Kallawar et al., 2023)
RhB	g-C ₃ N ₄ /BiOBr	Visible light	[RhB]o = 10 mg/L, pH = 7, t = 180 min, Catalyst dosage = 1 g/L	94.6 %	(Pan et al., 2022)
MG	GO/CuFe ₂ O ₄	Visible light	[MG]o = 10 mg/L, pH = 7, t = 200 min, Catalyst dosage = 0.01 g/L	90.7 %	(Yadav et al., 2021)
MB	S-GO-SnO ₂	Visible light	[MB]o = 50 mg/L, pH = 7, t = 120 min, Catalyst dosage = 0.2 g/L	> 90 %	(Pandiyan et al., 2019)
MO	RF@CeO ₂ -rGO	Visible light	[MO]o = 30 mg/L, pH = 8, t = 120 min, Catalyst dosage = 1 g/L	90 %	(Verma and Ananthakrishnan, 2020)
Victoria blue [VB]	GO-V ₂ O ₅	Sun light	[VB]o = 10 mg/L, pH = 8, t = 90 min, Catalyst dosage = 0.1 g/L	97.95 %	(Beaula Ruby Kamalam et al., 2021)

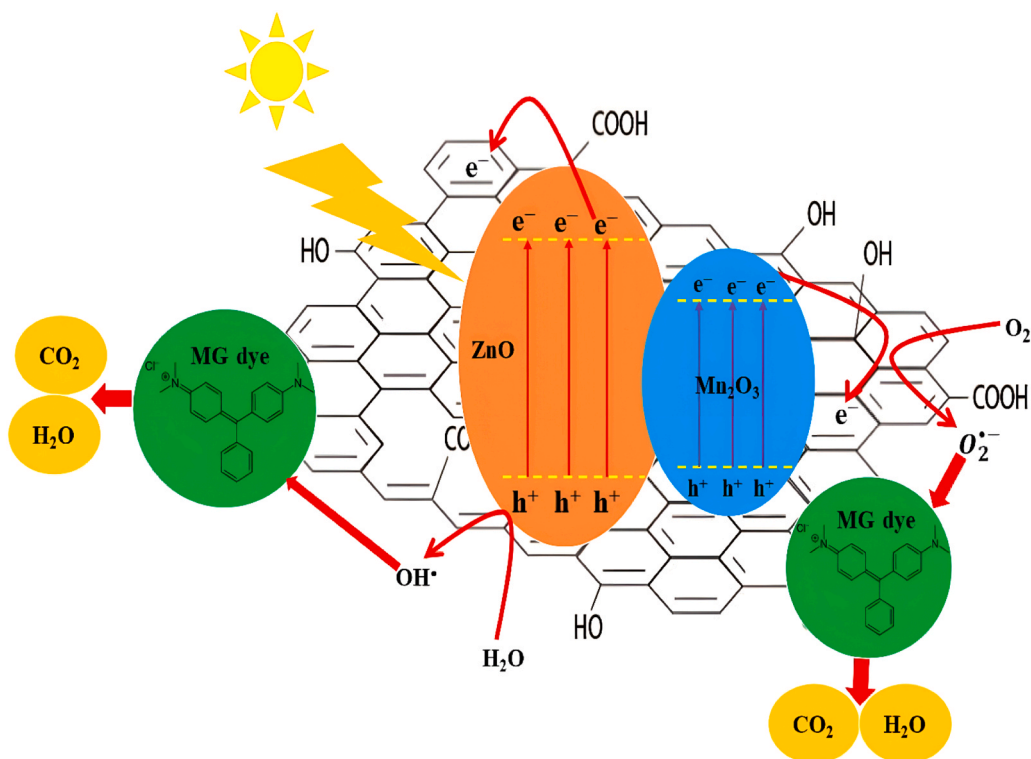


Fig. 7. Schematic diagram of MG dye degradation mechanism using GO-ZnO/Mn₂O₃ composite, Reprinted with permission from (Rout et al., 2022), copyright 2023 Elsevier, Licence no. 5881890051112.

irradiation duration 100 min. The bandgaps were estimated to be 1.85, 1.9, 1.94, and 2.8 eV for the CeO₂/Fe₂O₃/r-GO, CeO₂/Fe₂O₃, Fe₂O₃, and CeO₂ respectively. It is observable that the band gap energy value of CeO₂/Fe₂O₃/r-GO is decreased because of the addition of rGO on the surface of CeO₂/Fe₂O₃. It shows that the addition of 2-D graphene sheets augmented the photocatalytic performance. The enhanced degradation efficacy of the CeO₂/Fe₂O₃/r-GO catalyst was mostly due to the synergistic effects of the heterojunctions at the interface. The hydrothermal synthesis of a new NiMnO₃/NiMn₂O₄ - Graphene nanocomposite was carried out in order to appraise the photocatalytic degradation of MB dye when exposed to visible light (Chandiran and Nagamuthu Raja, 2023). The BET surface area of

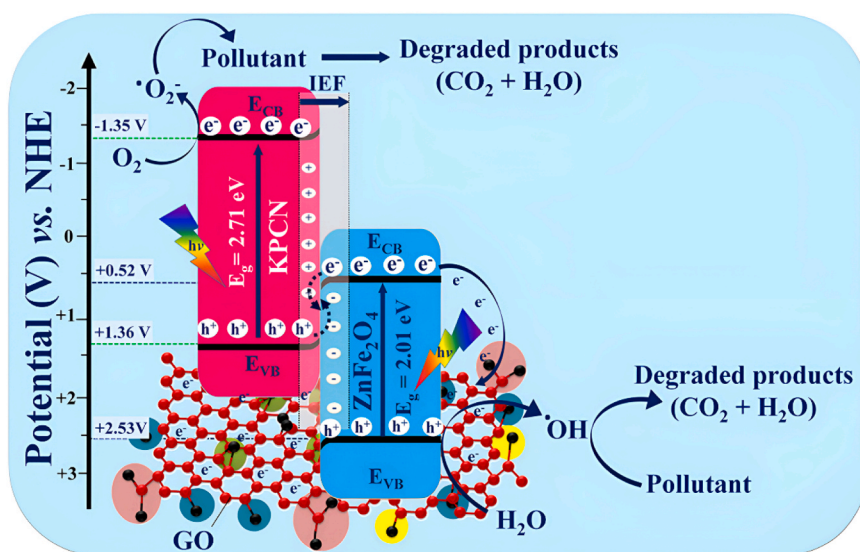


Fig. 8. Proposed mechanism of photocatalytic decomposition of pollutants by KPCN/GO/ZnFe₂O₄ photocatalyst, Reprinted with permission from (Kumar et al., 2023a), copyright 2023 Elsevier, License no. 5881920645300.

14.8 m²/g and bandgap energy of 1.2 eV have been obtained by BET surface area analyzer and UV–VIS DRS method. The optimized parameter conditions were pH 7, catalyst loading 0.2 g/L, initial level 10 mg/L and irradiation time 70 min. The optimal photocatalytic dye degradation performance occurs at a pH of 7, because of the electrostatic interaction amid the negatively charged MB dye molecules and the positively charged NiMnO₃/NiMn₂O₄–Graphene nanocomposite and likely serves as the primary adsorption mechanism. The NiMnO₃/NiMn₂O₄–Graphene nanocomposite exhibits enhanced photocatalytic efficacy, surpassing that of NiMnO₃/NiMn₂O₄, NiMnO₃, and NiMn₂O₄ achieving complete degradation of MB dye with 100 % efficacy in half an hour. The enhanced photocatalytic efficacy is attributed to reduced recombination of e[−]/h⁺ pairs, better visible-light absorption, and effective separation of photogenerated charge carriers (Zeng et al., 2022). Both the stability and the performance of repeated cycles are outstanding in the NiMnO₃/NiMn₂O₄–Graphene photocatalyst.

Iqbal et al. (2023) employed a straightforward sonication technique to create GO–CeO₂ nanocomposites utilizing an aqueous extract of Phoenix dactylifera fruit (Iqbal et al., 2023). Nanoparticles ranging in size from 6 to 12 nm in diameter were successfully isolated, and they exhibited a spherical shape. The synthesized GO–CeO₂ composite was exploited for the decomposition of MO (100 ppm) underneath visible light illumination. The GO/CeO₂ nanocomposite exhibits enriched degradation of MO dye compared to CeO₂ NPs. After 80 min of visible light exposure, the optimized nanocomposite with 30 % GO–CeO₂ obtained a photocatalytic degradation efficiency of 93 %, according to the experimental results. The catalyst's capacity to degrade MO remains at 88 % after five recycling runs, suggesting only a 5 % decrease in efficiency, according to the reusability study. A hydrothermal synthesis of a potassium, phosphorus/graphitic carbon nitride (KPCN) photocatalyst ameliorated with graphene oxide and heterostructured with zinc ferroelectric oxide (ZnFe₂O₄) was carried out by R. Kumar et al. (2023) (Kumar et al., 2023a). The fabricated photocatalyst was exploited for the degradation of MB dye, RhB dye, and tetracycline (TC) antibiotic. The degradation efficiency for RhB dye was 96 % after 30 min whereas for MB dye was 93 % after 120 min. In the photocatalytic process, •OH and •O₂[−] were the most reactive oxygen species, as verified by electron spin resonance and scavenging tests. After five consecutive regeneration cycles the results showed that only minimal degradation efficiency reduced which confirms the reusability of the catalyst. Fig. 8 shows the proposed mechanism of photocatalytic decomposition of contaminants by KPCN/GO/ZnFe₂O₄ photo-catalyst.

Table 6

Photocatalytic decomposition of phenolic contaminants using graphene-based photocatalyst materials.

Phenolic Pollutant	Catalyst	Energy Source	Operating Conditions	Photocatalytic Degradation (%)	References
BPA	ZnO/GO/Mn ₂ O ₃	Sun light	[BPA]o = 100 mg/L, t = 20 min, Catalyst dosage = 0.1 g/L, pH = 7	99.32 %	(Rout and Jena, 2023)
Phenol	TiO ₂ /rGO–4 %	Visible Light	[Phenol]o = 20 mg/L, t = 720 min, Catalyst dosage = 0.2 g/L, pH = 10	97.9 %	(Wang et al., 2020a)
Phenol	Fe-Fe ₃ O ₄ -GO	Sun light	[Phenol]o = 100 mg/L, t = 90 min, Catalyst dosage = 0.1 g/L, pH = 3	90 %	(Le et al., 2018)
p-Nitrophenol (p-NP)	W-doped TiO ₂ /rGO	Xenon lamp	[p-NP]o = 10 mg/L, t = 180 min, Catalyst dosage = 0.2 g/L, pH = 7	87 %	(Yadav et al., 2017)
BPA	B–TiO ₂ @GO	Sun light	[BPA]o = 10 mg/L, t = 240 min, Catalyst dosage = 1 g/L, pH = 7	47.66 %	(Altin et al., 2021)
4-NP	WS ₂ -rGO	Visible light	[4-NP]o = 20 mg/L, t = 30 min, Catalyst dosage = 0.4 g/L, pH = 7	96.95 %	(Ranjith Kumar et al., 2024)
BPA	TiO ₂ -ACD@rGO	UV light	[BPA]o = 10 mg/L, Catalyst dosage = 0.1 g/L, t = 60 min, pH = 7	86 %	(Wang et al., 2021)
BPA Bisphenol-F 2,4-DCP	Fe-PMS@GO	Visible light	[BPA]o = [BPF]o = [2,4-DCP]o = 20 μM, pH = 3, t = 60 min, Catalyst dosage = 0.2 g/L	BPA = 99 % BPF = 95 % 2,4-DCP = 95 %	(Cheng et al., 2020)
BPA	ZnO–CdO@rGO	UV light	[BPA]o = 10 mg/L, Catalyst dosage = 0.3 g/L, pH = 7, t = 120 min,	98.5 %	(Kumar et al., 2022a)
Phenol 2-CP 2-NP	Au–Pd/rGO	Sun light	[Phenol]o = [2-CP]o = [2-NP]o = 0.5 mM, [Phenol]t = 300 min, [2-CP]t = [2-NP]t = 180 min, pH = 9 for 2-NP, pH = 7 for 2-CP and phenol, Catalyst dosage = 0.5 g/L	Phenol = 94.4 % 2-CP = 97 % 2-NP = 98.6 %	(Darabdhara et al., 2016)
Phenol	Ag–MgAl ₂ O ₄ @rGO	Sun light	[Phenol]o = 10 mg/L, pH = 7, t = 135 min, Catalyst dosage = 0.01 g/L	40.51 %	(Farooq et al., 2023)
BPA p-bromophenol (p-BP)	n-ZnO/n-SnO ₂	Visible light	[BPA]o = [p-BP]o = 10 mg/L, pH = 7, t = 180 min, Catalyst dosage = 0.6 g/L	p-BP = 98.64 % BPA = 98.5 %	(Kumar et al., 2023b)
p-NP	rGO@ZnO	UV light	[p-NP]o = 0.1 mM, pH = 7, t = 4 min, Catalyst dosage = 0.15 mg	98 %	(Velusamy et al., 2023)
4-NP	Pt loaded ZnO-RGO	Sun light	[4-NP]o = 0.1 mM, pH = 9, t = 7 min, Catalyst dosage = 2 g/L	92 %	(Kumar et al., 2018)
p-NP	Cu ₂ O/ZnO/rGO	Sun light	[p-NP]o = 10 mg/L, pH = 7, t = 90 min, Catalyst dosage = 0.3 g/L	98 %	(Liu et al., 2019)
Phenol	rGO-NiO/CdO	Visible light	[Phenol]o = 10 mg/L, pH = 7, t = 90 min	89.6 %	(Ceril Jeoffrey et al., 2023)
BPA	MoO ₃ /ZnO/GO	Visible light	[BPA]o = 1 mg/L, pH = 8, Catalyst dosage = 0.2 g/L t = 180 min,	70 %	(Moslan et al., 2023)

Nie et al. (2023) have developed a heterojunction photocatalyst with HNO_3 protonated C_3N_4 and GO-derived GOQDs (GOQDs/ $\text{Hp-C}_3\text{N}_4$) via electrostatic self-assembly (Nie et al., 2023). The surface area and band gap energy of GOQDs/ $\text{Hp-C}_3\text{N}_4$ were $33.634 \text{ m}^2/\text{g}$ and 2.367 eV respectively. The synthesized GOQDs/ $\text{Hp-C}_3\text{N}_4$ degrades 99 % of MO dye in 105 min of LED irradiation. Compare to GO/ $\text{Hp-C}_3\text{N}_4$, $\text{Hp-C}_3\text{N}_4$, and C_3N_4 the decomposition efficacy of the GOQDs/ $\text{Hp-C}_3\text{N}_4$ for MO degradation was increased by 4, 9, and 343 times. The scavenger study shows that the reactive species on the degradation of MO by GOQDs/ $\text{Hp-C}_3\text{N}_4$ are in the order of $\text{h}^+ < \bullet\text{O}_2^- < \bullet\text{OH}$. The favorable parameter conditions were catalyst loading 1 g/L , initial MO dye level 10 mg/L , pH 7, and irradiation duration 105 min. Pan et al. (2022) produced a recyclable rGO/chitosan (CS) composite aerogel supported g- $\text{C}_3\text{N}_4/\text{BiOBr}$ photocatalyst for RhB dye degradation (Pan et al., 2022). In this composite, borax was used as a crosslinking agent and on the matrix of rGO and CS g- $\text{C}_3\text{N}_4/\text{BiOBr}$ was loaded. The synthesized g- $\text{C}_3\text{N}_4/\text{BiOBr}$ photocatalyst degrades 94.6 % RhB dye at 180 min under pH = 7. The photocatalytic activity was further augmented by the composite photocatalyst of g- $\text{C}_3\text{N}_4/\text{BiOBr}$, which successfully inhibited the recombination of e^-/h^+ pairs placed on the rGO matrix. The recyclability study revealed that after 4 cycles the degradation rate was about 80 %. The scavenger study showed that h^+ and $\bullet\text{O}_2^-$ were the active substances which effectively degrades the RhB dye into harmless product.

7.2. Photocatalytic degradation of phenolic pollutants

Phenolic pollutants are categorized as organic compounds featuring benzene rings linked to other aromatic compounds that possess hydroxyl groups. Phenolic pollutants are high-priority pollutants because of the harm they do to human health, says the US Environmental Protection Agency (EPA) (Grace Pavithra et al., 2023). However, the hazardous effects of phenol exposure on people and animals ranged from 9 to 25 mg/L. Strict limitations are applied to phenol discharge due to its high reactivity or tendency to interrelate with other chemicals in the water system. Phenol was regarded as a dangerous agent due to its capacity to induce both acute and chronic health issues. Extended exposure may result in tremors, loss of consciousness, respiratory failure, and abnormal breathing patterns. Injuries to the skin, lungs, kidneys, liver, and digestive systems are symptoms of phenol and chlorophenol poisoning (Rout and Jena, 2022a). Due to its toxicity, corrosiveness, and carcinogenic properties, phenol must be strictly avoided (Xiong et al., 2021). Biodegradation may be impeded when effluent concentrations above 50 mg/L (Saputera et al., 2021). The effluents produced by many industrial sectors, including petroleum, pharmaceuticals, refineries, plastics, coking, fertilizers, and home trash, are characterized by elevated levels of phenols (Sathya et al., 2022). Humans can absorb phenol through the skin or ingestion, with the latter facilitating absorption into the gastrointestinal tract. Upon metabolism, phenol is converted into several intermediates, including quinone derivatives (Anku et al., 2017). Both humans and animals are particularly vulnerable to the endocrine-disrupting impacts of BPA and alkylphenols on the mammary glands (Muñoz-de-Toro et al., 2005). Phenol concentrations in bottled water should not exceed 0.001 mg/L, while those in groundwater should not exceed 0.01 mg/L, according to the USFDA (Food and Drug Administration) (Rout and Jena, 2022b). Therefore, the level of phenolic contaminants in waters must be diminished prior to its release into the environment. Photocatalytic degradation of phenolic contaminants such as Phenol, Bisphenol-A (BPA), Cresol, 2,4,6 - Trichlorophenol (2,4,6-TCP), 2,4 - Dichlorophenol (2,4-DCP), 2 - Chlorophenol (2-CP), 2 - nitrophenol (2-NP), etc.... by these materials are discussed in this

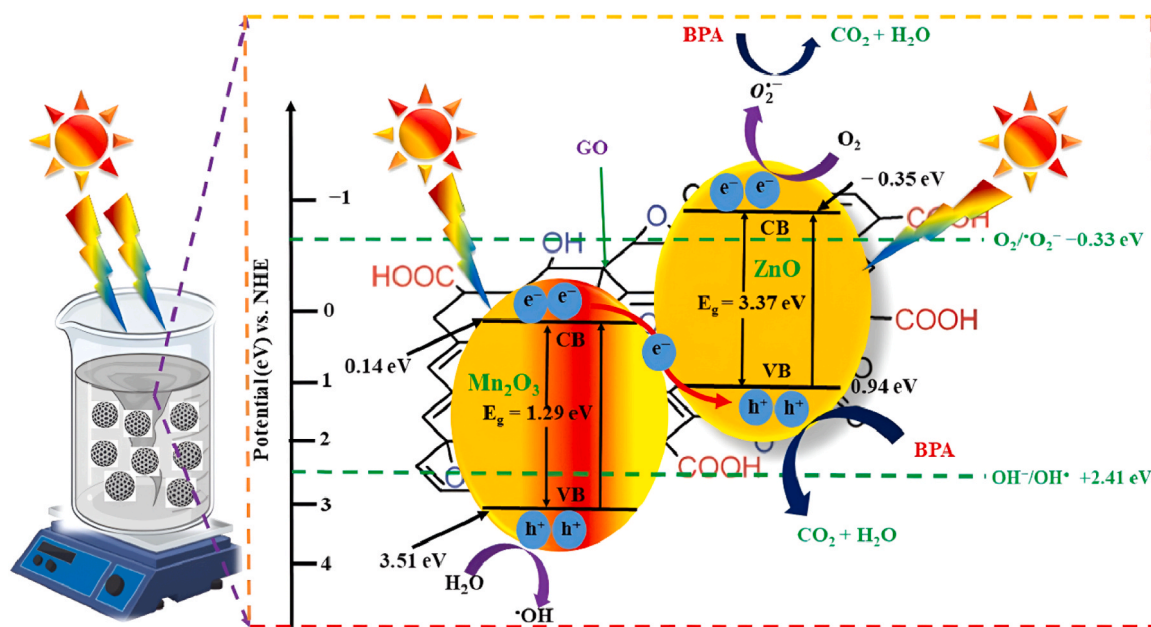


Fig. 9. Z-scheme mechanism of $\text{ZnO}/\text{GO}/\text{Mn}_2\text{O}_3$ composite in the BPA degradation, Reprinted with permission from (Rout and Jena, 2023), copyright 2023 Elsevier, License no. 5881900518573.

section.

A range of graphene-based composites has been utilized for the photodegradation of phenolic contaminants in wastewaters, as outlined in Table 6. Rout and Jena, (2023) reported that BPA degradation by using Z-scheme ternary composite ZnO/GO/Mn₂O₃ under sunlight irradiation involves various stages of degradation (Rout and Jena, 2023). The degradation time is reported as 20 min, pH 7, catalyst dose 0.1 g/L, and BPA level 100 mg/L. Analysis of free radical capture studies revealed that the primary reactive species responsible for degradation were $\cdot\text{O}_2^-$ and h^+ , with efficiencies of 91.23 % and 95.16 %, respectively. From the kinetic data it can be seen that the pseudo-first-order exhibits best fitted model. The rate constant (0.201 min^{-1}) is 4.08, 14.28, and 22.22 times greater than that of ZnO/GO, GO, and Mn₂O₃ respectively. The improved catalytic activity resulted from the formation of an effective Z-scheme heterojunction, facilitating the separation of e^-/h^+ pairs and so augmenting the concentration of reactive species in the solution. After five successive cycles, the recycling trials revealed that just 10.85 % of the degradation had been mitigated. Fig. 9 shows the BPA degradation mechanism using ZnO/GO/Mn₂O₃ composite. The mechanism shows that the metallic semiconductor generates electron-hole pair when light falls on the photocatalyst surface. G. Wang et al. (2020) synthesized a hybridized TiO₂/rGO composites for the photocatalytic decomposition of phenol underneath visible light illumination (Wang et al., 2020a). The decomposition time is reported as 720 min, pH 10, and catalyst dosage 0.2 g/L and initial phenol concentration 20 mg/L. Among the TiO₂/rGO nanocomposites, TiO₂/rGO-4 % exhibited the strongest photocurrent response. With a bandgap of 2.91 eV, this nanocomposite redshifted its absorption into the visible region, leading to its high photocatalytic performance underneath visible light ($\lambda > 420 \text{ nm}$). In addition, the samples were used to break down phenol solutions when exposed to visible light. With a degradation rate constant of 0.0190 h^{-1} , the TiO₂/rGO-4 % nanocomposite outperformed other TiO₂/rGO nanocomposites in terms of phenol solution degradation, reaching a maximum degradation rate of 97.9 %.

Le et al. (2018) used the precipitation method and chemical reduction with NaBH₄ as the reducing agent and FeCl₃ as the iron source to successfully manufacture a new nano-Fe-Fe₃O₄-GO composite (Le et al., 2018). Following 90 min of reaction underneath simulated sunshine illumination, the conversion attained 75 % for the Fe₃O₄-GO and 87 % for Fe-Fe₃O₄-GO composite, respectively. The catalyst exhibited excellent stability as well; hence, 84 % conversion persisted following three cycles. The degradation time is reported as 90 min, pH 3, catalyst dosage 0.1 g/L, and initial phenol concentration 100 mg/L. Because of the synergistic impact of the Fe/Fe₃O₄ species, the presence of nano-Fe and Fe₃O₄ particles results in a high catalytic activity. Because of its great stability and magnetism, this Fe-Fe₃O₄-GO composite is also easily recoverable and reusable. Yadav et al. (2017) propose a hybrid approach to mitigate surface and bulk recombination by doping TiO₂ with tungsten and creating a composite with rGO (Yadav et al., 2017). Incorporating W⁶⁺ into the TiO₂ crystal lattice generates an impurity level situated just beneath the conduction band, which acts as a site for electron entrapment, prolonging the duration of photo induced charge carriers. The nanocomposites exhibit 87 % degradation of p-nitrophenol under various optimized methods, significantly outperforming single materials or binary composites. Photoluminescence and X-ray photoelectron spectroscopy studies demonstrate that tungsten functions as an electron trap, hence reducing interband recombination. The interaction between rGO and TiO₂ facilitates a pathway for rapid electron excitation transfer before recombination occurs at surface defect sites. The degradation of BPA under solar light conditions was successfully achieved by incorporating boron-doped titanium dioxide on GO (denoted as B-TiO₂@GO) through a hydrothermal treatment (Altin et al., 2021). The optimized conditions were catalyst dose 1 g/L, BPA level 10 mg/L, pH = 7, and irradiation time is 240 min. The degradation of BPA exhibited a general trend in the kinetic constants with the addition of B-TiO₂@GO photocatalysts: an increase was noted with a higher TiO₂ content in B-TiO₂@GO (ranging from 0.5 % to 2 % TiO₂ mass), while the lowest value was recorded for the B-TiO₂ catalyst, indicating the substantial influence of the direct interaction between the photocatalyst and substrate occurring at the catalyst surface. The results further validated that the photocatalytic rate is significantly influenced by both B-doping and the presence of GO.

Hydrothermal synthesis of sulfur vacancy caused WS₂-rGO heterostructures was carried out by Ranjit Kumar et al., (2024). The WS₂/rGO heterostructure exhibited excellent photocatalytic activity towards 4-nitrophenol with a kinetic rate constant of 0.113 min^{-1} , which is 22 folds greater than that of pristine WS₂. The WS₂/rGO heterostructure degrades 96.95 % of 4-nitrophenol (4-NP) in 30 min. Distinct TiO₂@aspartic acid β -cyclodextrin@reduced graphene oxide (TiO₂-ACD@rGO) nano photocatalysts were effectively synthesized using a photochemical method and examined for their photocatalytic efficacy in the elimination of BPA under ultraviolet irradiation (Wang et al., 2021). The degradation rates were in this order: TiO₂ < TiO₂@rGO < TiO₂-ACD@rGO. Following 60 min of UV exposure, the degradation rate of BPA by TiO₂-ACD@rGO attained 86 %, surpassing that of TiO₂@rGO and TiO₂ by roughly 10 % and 25 %, respectively. The optimized parameter conditions were pH 7, initial BPA concentration 10 mg/L, and catalyst loading 0.1 g/L. TiO₂@ACD@rGO has a reaction constant of 0.739 mg/L.min for BPA, which is 1.34 times higher than TiO₂@rGO and 1.87 times greater than TiO₂. Photogenerated electrons are caught and transmitted by TiO₂-ACD@rGO, which has a comparatively high active surface area of 82.8 m²/g. This, in turn, stimulates charge separation, which could explain the findings. ACD might build host-guest complexes with BPA by molecular recognition, hence enhancing the sorption of BPA on the photocatalyst surface. In conclusion, both ACD and rGO facilitate the photocatalytic breakdown of BPA.

Darabdhra et al. (2016b) have effectively synthesized rGO nanosheets adorned with Gold-Palladium bimetallic alloy nanoparticles by a chemical method that involves the reduction of metals using ascorbic acid. The synthesized substance facilitates the decomposition of phenolic derivatives in sunlight. Degradation efficiencies of 94.40, 97, and 98.6 % were obtained for phenol, 2-CP, and 2-NP at optimized parameter conditions such as catalyst dosage 0.5 g/L, initial concentration 0.5 mM, pH for 2-CP and phenol were 7 and for 2-NP it was 9. The degradation kinetics follow a linear Langmuir-Hinshelwood model with rate constant 0.0078 min^{-1} for phenol, 0.0078, 0.0172, and 0.0181 min^{-1} for phenol, 2-CP, and 2-NP respectively. Moreover, the photocatalyst has outstanding stability and can be reused up to five cycles. A nanocomposite consists of ZnO-CdO nanoparticles modified with reduced graphene oxide (ZnO-CdO@rGO) were prepared by a simple refluxing procedure and employed for the degradation of BPA under UV irradiation (Kumar et al., 2022a). The maximum efficiency of 98.5 % occurred by using ZnO-CdO@rGO composite under UV light irradiation. The

optimized parameter conditions were pH 7, initial BPA level 10 mg/L, and irradiation duration 120 min. The kinetic rate constant for this BPA degradation using ZnO–CdO@rGO composite was 0.0088 min^{-1} . Kumar et al. (2023) synthesized a superior n-ZnO/n-SnO₂ heterojunction integrated with rGO nanosheets, which was evaluated for the removal of several organic contaminants, namely p-bromophenol and BPA (Kumar et al., 2023b). Using a simple refluxing process, the ZnO/SnO₂ heterojunction was functionalized with varying weight percentages of rGO. The peak photocatalytic efficiency of the nanocomposite containing 5 wt% rGO was recorded at around 98.50 % and 98.64 % for the degradation of BPA and p-bromophenol respectively, following 180 min of UV light exposure. The optimized parameter conditions were initial p-bromophenol and BPA level 10 mg/L, catalyst dosage 0.6 g/L and initial pH = 7.0. The exceptional photocatalytic performance of the nanocomposite containing 5 wt% rGO is evidenced by the existence of homotypic ZnO/SnO₂ and rGO, attributable to their synergistic interaction. This interaction facilitates significant charge carrier separation, leading to an increased generation rate of O₂ and improved photodegradation of p-bromophenol and BPA. Fig. 10 shows the plausible degradation mechanism of p-bromophenol and BPA using n-ZnO/n-SnO₂ composite.

Farooq et al. (2023) have fabricated the Ag-doped MgAl₂O₄@rGO using the coprecipitation method followed by sonication (Farooq et al., 2023). The band gap energy value decreases from 2.55 to 2.40 eV, and the visible light harvesting ability is substantially improved by doping. In contrast to Ag-MAO, and MAO the Ag-MAO@rGO photocatalyst exhibited exceptional degradation efficiency. The increased activity of Ag-MAO@rGO was assigned to the existence of rGO and silver ions in the synthesized nanocomposite. The degradation efficiency of organic effluent is enhanced by the increased surface area provided by reduced graphene oxide. Ag-MAO@rGO possesses the capability to function as a photocatalyst for environmental remediation. In a different research, the enhanced photocatalytic performance of the Fe(III)/peroxymonosulfate (Fe–PMS@GO) process for getting rid of BPA, bisphenol-F (BPF), and 2,4-DCP were looked at (Cheng et al., 2020). This work reports that GO is an exceptional accelerant for improving the redox cycle of Fe(III)/Fe(II) underneath visible light illumination. The photocatalyst can eliminate 99 % of BPA in 60 min and possesses extensive oxidative capability for decomposing various organic contaminants. According to ESR analysis and scavenger study, it can be observed that both OH[•] and SO₄^{•-} are responsible for BPA degradation. A reduction mechanism for Fe(III) was postulated based upon the analysis of Fe mass balance. Fe(II) is mostly present in the form of GO-Fe(II) complex resulting from GO's reduction of the GO-Fe(III) complex by means of the intramolecular electron transition, therefore exposing the iron cycle mostly on GO surface. Another benefit of using GO is that some of the Fe(II) that is produced there can be released into the water to create a cycle of dissolved Fe(III)/Fe(II). An integral part of the process, GO speeds up the Fe(III)/Fe(II) cycle and increases free radical yields, which aid in pollution removal. The schematic diagram of BPA degradation using Fe–PMS@GO composite was shown in Fig. 11.

7.3. Degradation of pharmaceutical pollutants

When it comes to treating a wide range of illnesses in both humans and animals, antibiotics are by far the most used family of drugs.

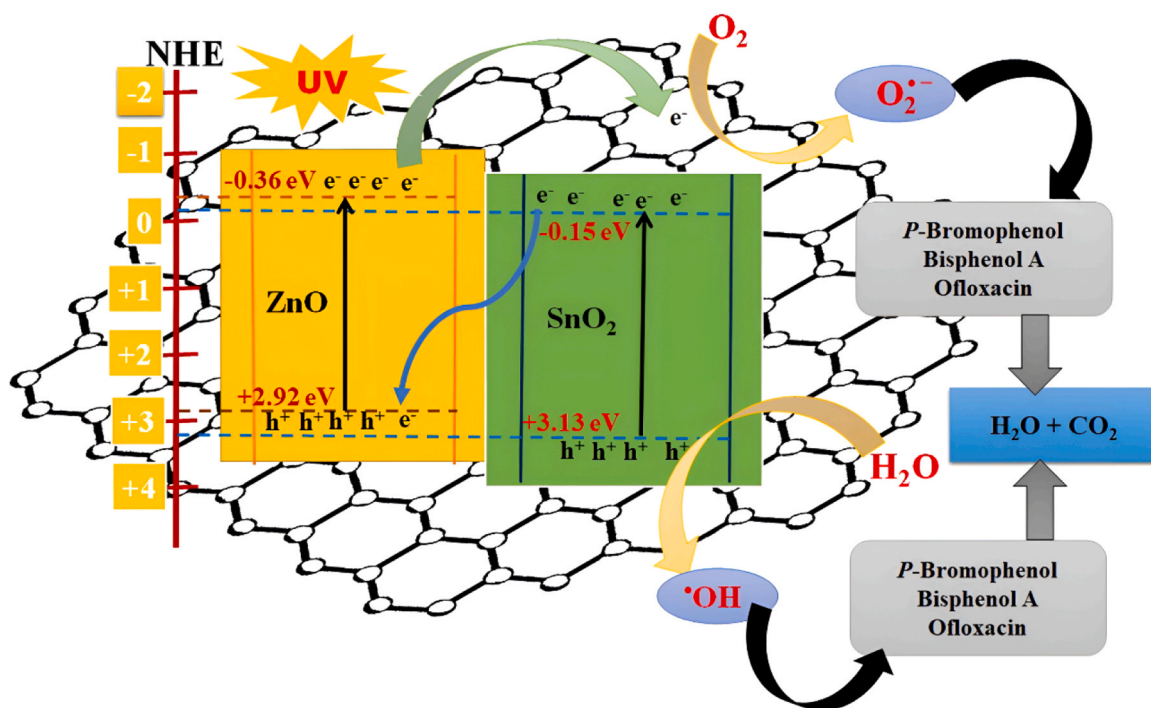


Fig. 10. The plausible degradation mechanism of p-bromophenol and BPA using n-ZnO/n-SnO₂ composite, Reprinted with permission from (Kumar et al., 2023b), copyright 2023 Elsevier, License no. 5881930309147.

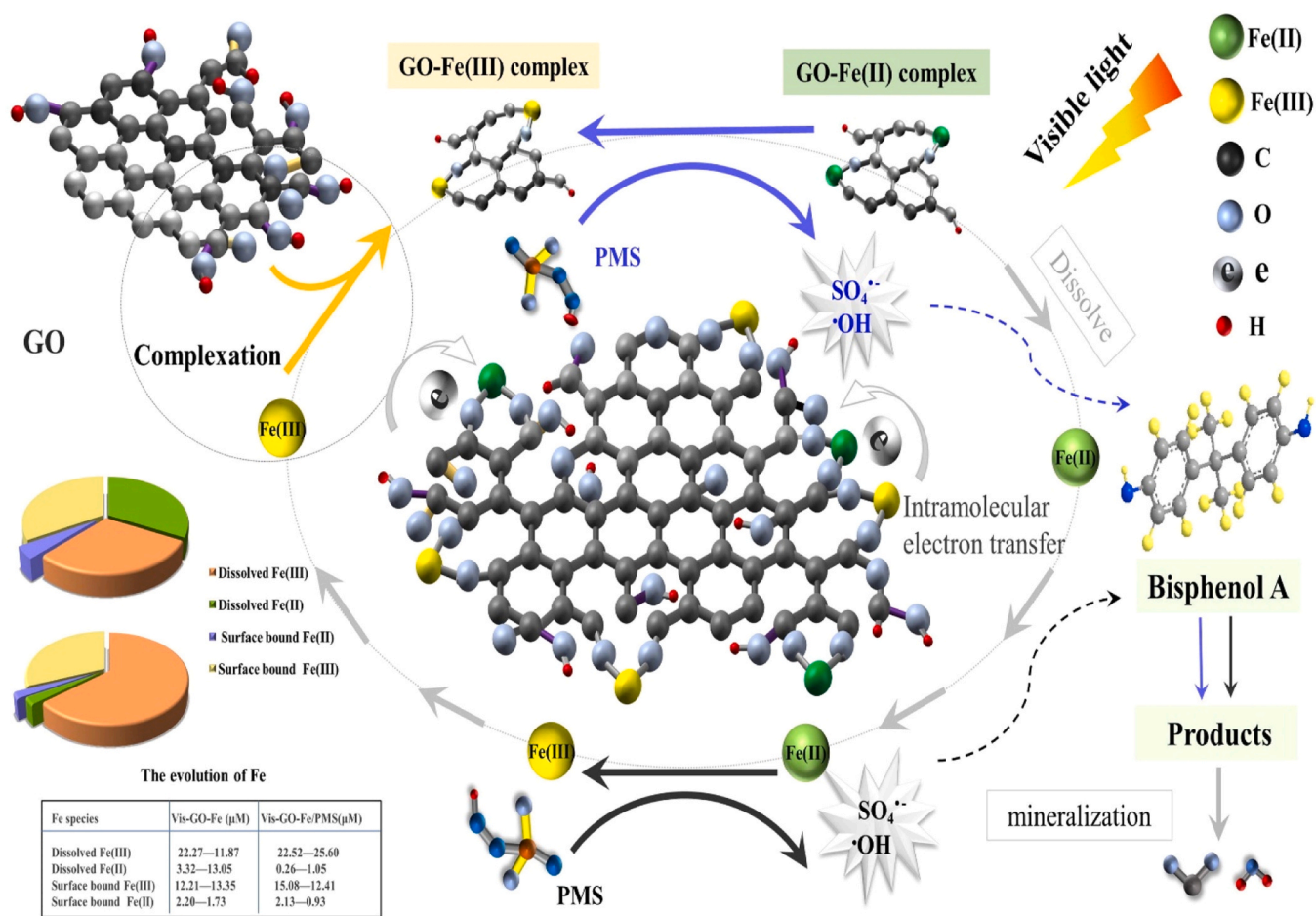


Fig. 11. Schematic diagram of the reaction mechanism of the Vis-GO-Fe/PMS system, Reprinted with permission from (Cheng et al., 2020), copyright 2023 Elsevier, License no. 5882900941243.

A growing amount of antibiotics have been detected in several sources, including surface water, drinking water, groundwater, and animals, as a result of the persistent discharge of antibiotics (Maghsodian et al., 2022). Wastewater from antibiotic producers, industrial animal farms, and healthcare facilities is the primary contributor to this pollution in waterways. As a consequence, antibiotics like ampicillin, erythromycin, levofloxacin, sulfamethoxazole, ciprofloxacin, ofloxacin have been traced in water species such as algae, crustaceans, fish, bacteria, rotifers, etc... (Ebele et al., 2017). Florfenicol, oxytetracycline, doxycycline, and azithromycin are more lethal to algae than cefotaxime and amoxicillin (Fu et al., 2017). Ofloxacin influences the physiological mechanisms of algal photochemistry and antioxidant systems, leading to reduced algal cell growth, photosynthetic efficiency, and chlorophyll levels. A decrease in chlorophyll content hinders metabolic processes and photosynthesis, which in turn restricts the growth and multiplication of cells. The methyl ester of carbohydrates and fatty acids can be reduced in *S. obliquus* by sulfamethazine and sulfamethoxazole (Xiong et al., 2019). The most susceptible species to oxytetracycline, with an EC₅₀ value of 3.26 mg/L, is duckweed, however it also causes growth harm and reproductive damage in algae (*S. vacuolatus*) and crustaceans (*D. magna*). Exposure to tetracycline (TC) caused photo-inhibition of *V. fischeri*, and the resulting degradation product was more toxic than the original compound (Sharma et al., 2022). The metabolism of *Carassius auratus*, both in the liver and outside the liver, can be affected by roxithromycin and its physiologically active byproducts (Ramos-Sosa et al., 2022). A multi-pronged strategy incorporating correct disposal techniques and reducing antibiotic release into the environment is necessary to address the antibiotics' ecotoxicology impact for the benefit of humans, plants, and animals.

Numerous composites based on graphene have been used for the photodegradation of pharmaceutical pollutants and are summarized in Table 7. Lu and colleagues reported the production of a novel Z-scheme photocatalyst g-C₃N₄/rGO/WO₃ by the photo-reduction procedure for ciprofloxacin (CIP) degradation (Lu et al., 2019). The PL and EIS investigation results revealed that the synthesized catalyst g-C₃N₄/rGO/WO₃ exhibited superior charge separation and increased electron mobility compared to g-C₃N₄, g-C₃N₄/WO₃, and WO₃. The dimensions of the produced nanocomposite range from 50 to 150 nanometers. The optimized parameter conditions were time 180 min and catalyst amount 0.2 g/L. Photocatalytic investigations indicated that g-C₃N₄/rGO/WO₃ demonstrated superior photocatalytic efficacy for CIP degradation, achieving up to 80 % under visible light. The unique electron and hole transport mechanism in the Z-scheme system enables g-C₃N₄/rGO/WO₃ to exhibit enhanced oxidation and reduction capabilities, facilitating the creation of diverse reactive species for the decomposition of CIP. Wang et al. (2020) have synthesized TiO₂ and iron-oxide co-doped GO nanosheets (TiO₂/Fe₂O₃/GO) by a self-assembly procedure for CF degradation (Wang et al., 2020b). Characterization studies revealed that produced TiO₂/Fe₂O₃/GO nano-sheets possess narrow band-gap energies and high structural stability. The integration of TiO₂ significantly improves catalytic activity, achieving approximately 99 % degradation of CF in 140 min under visible light irradiation. The synthetic photocatalyst is capable of being reused for a maximum of four cycles.

A graphene-SBA/TiO₂ photocatalyst was synthesized by combining a hydrothermal procedure for TC degradation with a straightforward sol-gel co-condensation method (Ali et al., 2021). Nanocomposite has a pore volume of about 5–10 nm and a surface area of 310–340 m²/g. Within 30 min of being exposed to visible light, 98 % of the TC had been broken down. The ability of the SBA/TiO₂ to absorb aromatic chemicals through π - π stacking interaction is exceptional. Vinesh et al. (2019) documented the production of the Au/B-TiO₂/rGO composite for TC decomposition underneath visible light (Vinesh et al., 2019). The addition of Au and e⁻ deficient B atoms to TiO₂ has significantly improved optical absorption in the visible spectrum. The improved degrading might be

Table 7
Graphene based photocatalyst for degradation of pharmaceuticals.

Pharmaceutical Pollutant	Catalyst	Energy Source	Operating Conditions	Photocatalytic Degradation (%)	References
CIP	g-C ₃ N ₄ /rGO/WO ₃	Visible light	[CIP] ₀ = 10 mg/L, t = 180 min, Catalyst dosage = 0.2 g/L	80 %	(Lu et al., 2019)
Sulfamethoxazole	α -Fe ₂ O ₃ /rGO	Visible light	[Sulfamethoxazole] ₀ = 20 mg/L, t = 45 min, Catalyst dosage = 0.025 g/L	99.9 %	(Asif et al., 2023)
TC	α -Fe ₂ O ₃ /rGO	LED light	[TC] ₀ = 5 mg/L, pH = 7, t = 140 min, Catalyst dosage = 5 g/L	99 %	(Shibu et al., 2022)
CIP	Ag ₂ CrO ₄ /Ag/BiFeO ₃ /rGO	Visible light	[CIP] ₀ = 0.5 mg/L, pH = 8, t = 90 min, Catalyst dosage = 0.3 g/L	96.3 %	(Kumar et al., 2019)
TC	MoS ₂ /Ag/GO	Visible light	[TC] ₀ = 10 mg/L, pH = 8, t = 120 min, Catalyst dosage = 0.25 g/L	90.7 %	(Monga and Basu, 2022)
CIP	TiO ₂ /Fe ₂ O ₃ /GO	Xenon lamp	[CIP] ₀ = 10 mg/L, pH = 6.6, t = 140 min, Catalyst dosage = 0.4 g/L	99 %	(Wang et al., 2020b)
Norfloxacin(NF)	rGO/Bi ₂ WO ₆	UV light	[NF] ₀ = 10 mg/mL, pH = 4.75, t = 180 min, Catalyst dosage = 0.5 g/L	87.49 %	(Zhao et al., 2021)
CIP	Bi ₂ Ti ₂ O ₇ /TiO ₂ / rGO	Solar light	[CIP] ₀ = 10 mg/L, pH = 7, t = 180 min, Catalyst dosage = 0.25 g/L	95 %	(Li et al., 2020)
Azithromycin	GO@Fe ₃ O ₄ /ZnO/SnO ₂	UV light	[Azithromycin] ₀ = 30 mg/L, pH = 3, t = 120 min, Catalyst dosage = 1 g/L	90.6 %	(Sayadi et al., 2019)
Metronidazole	CeM/GO	Visible	[Metronidazole] ₀ = 20 mg/L, pH = 5, t = 50 min, Catalyst dose = 0.5 g/L	99 %	(Karthik et al., 2017)
TC	MGO-Ce-TiO ₂	Visible	[TC] ₀ = 25 mg/L, pH = 5, t = 60 min, Catalyst dose = 0.5 g/L	82.92 %	(Cao et al., 2016)
TC	rGO-CdS/ZnS	Visible	[TC] ₀ = 15 mg/L, t = 60 min, Catalyst dose = 0.5 g/L	85 %	(Tang et al., 2015)

due to the synergistic influence of swift e^-/h^+ pair separation facilitated by e^- deficient B atoms and rGO. Parasuraman and colleagues have synthesized $\text{Bi}_2\text{S}_3/\text{BiWO}_6/\text{rGO}$ ternary nanocomposites by simple hydrothermal strategy for the TC degradation under visible light (Parasuraman et al., 2023). The $\text{Bi}_2\text{S}_3/\text{BiWO}_6/\text{rGO}$ nanocomposite exhibit enhanced photocatalytic activity compared to rGO, BiWO_6 , Bi_2S_3 , and $\text{Bi}_2\text{S}_3/\text{BiWO}_6$ photocatalysts. The degradation efficiency of TC medication using the ternary $\text{Bi}_2\text{S}_3/\text{BiWO}_6/\text{rGO}$ composites over 120 min was 86 %. The free radicals trapping experiments identified the $\cdot\text{O}_2^-$ and e^- as the significant active species. Another encouraging approach for wastewater treatment is the ternary nanocomposites of $\text{Bi}_2\text{S}_3/\text{BiWO}_6/\text{rGO}$, which showed remarkable promise in eliminating a ample range of pollutants from different water matrices. The hypothesized photocatalytic mechanism of the $\text{Bi}_2\text{S}_3/\text{BiWO}_6/\text{rGO}$ nanocomposites for TC degradation is schematically illustrated in Fig. 12.

Using a hierarchical method, a new ternary nanostructure was created for doxycycline (DOX) degradation when exposed to visible light. The structure consists of titania (TiO_2) and graphene quantum dots (GQDs)/zeolitic imidazolate framework-8 (ZIF-8) (Rabeie and Mahmoodi, 2023). The optimized parameter conditions were initial DOX concentration 220 mg/L, pH 7, catalyst dose 0.1 g/L, and irradiation duration 210 min. This photocatalytic degradation process was dominated by $\cdot\text{O}_2^-$ radicals, according to the research, and the ternary composite in question exhibited zero-order kinetics. Roy et al. (2023) generated a new ferrocene-functionalized rGO-ZnO composite using the simple hydrothermal technique (Roy et al., 2023). The Fc@rGO-ZnO composite was utilized for the decomposition of pharmaceuticals CIP and sulfamethoxazole (SMX) in water media underneath UV radiation. The synthesized Fc@rGO-ZnO photocatalyst exhibited a fivefold enhancement in removal efficiency compared to pure ZnO. This higher performance was ascribed to the greater light absorption, charge carrier interface, and improved charge separation. Furthermore, the photocatalyst conformed to the Lagergren model, i.e. pseudo-first-order kinetic model. The combined method utilizing Fc@rGO and ZnO as oxidizing agents effectively eliminated over 95 % of CIP and SMX within 180 min. Moreover, the heterostructure arrangement established betwixt Fc@rGO and ZnO facilitates charge movement and the production of a substantial quantity of $\cdot\text{O}_2^-$ and $\cdot\text{OH}$ radicals for photodecomposition processes. Yadav and colleagues documented the biogenic production of $\text{Cu}_2\text{O}/\text{rGO}$ utilizing orange peel as both reduction and stabilization agents for the breakdown of DOX (Yadav et al., 2023). The biogenically produced $\text{Cu}_2\text{O}/\text{rGO}$ nanocomposites shown exceptional catalytic efficacy, achieving a degradation efficiency of 98.68 % in 15 min and 86.38 % in 30 min for a 10 mg/L dye concentration, facilitated by ultrasonic waves and sun light in distinct processes. The entire degradation process adhered to pseudo-first-order kinetic model, with a rate constant of 0.0542 min^{-1} . According to the surface area analysis, the decomposition of DOX rises as the amount of GO increases. The optimized parameter conditions were DOX concentration = 10 mg/L; Catalyst loading = 0.1 g/L; pH = 7. This photocatalyst provides a straightforward, cost-effective, and time-efficient procedure for water filtration.

The $\text{GO-BiVO}_4\text{-ZnO}$ ternary photocatalyst has been synthesized by solvothermal procedure for the degradation of CIP underneath visible light illumination by (Raja et al., 2020). The produced ternary nanocomposite demonstrated 98.4 % decomposition of CIP in 60 min exhibiting remarkable reusability, with a band gap value of 2.35 eV. Photogenerated holes significantly contribute to the degradation of CIP. Despite six trials, the decomposition of CIP exceeded 90 %, demonstrating the exceptional reusability of the catalyst for practical applications. The proposed path for the photocatalytic decomposition of CIP utilizing the $\text{rGO-BiVO}_4\text{-ZnO}$ nanocomposite is illustrated in Fig. 13. Gao et al. (2021) have created $\text{NiAlCeLDH}/\text{RGO}$ composite trough one-step hydrothermal

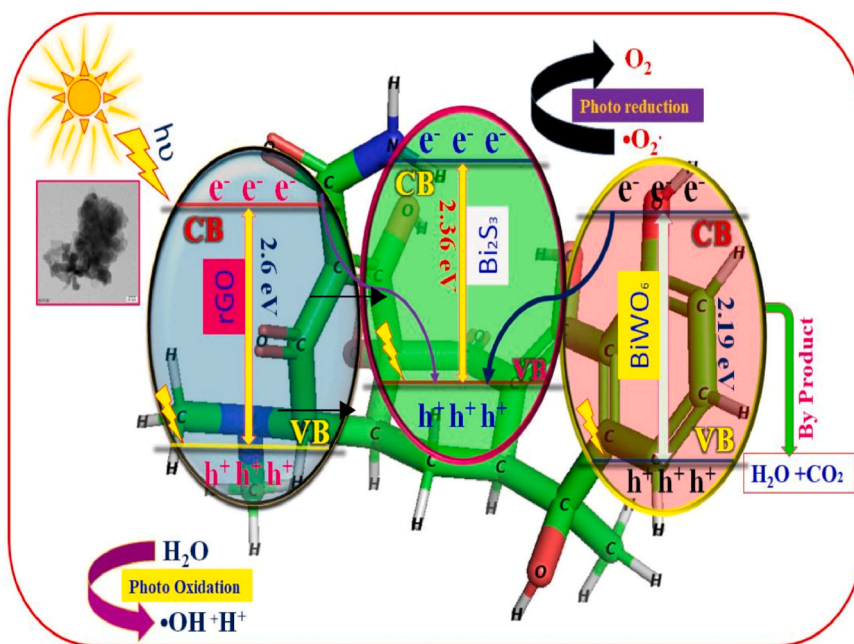


Fig. 12. Schematic diagram of $\text{Bi}_2\text{S}_3/\text{BiWO}_6/\text{rGO}$ nanocomposites for TC degradation, Reprinted with permission from (Parasuraman et al., 2023), copyright 2023 Elsevier, License no. 5882910321524.

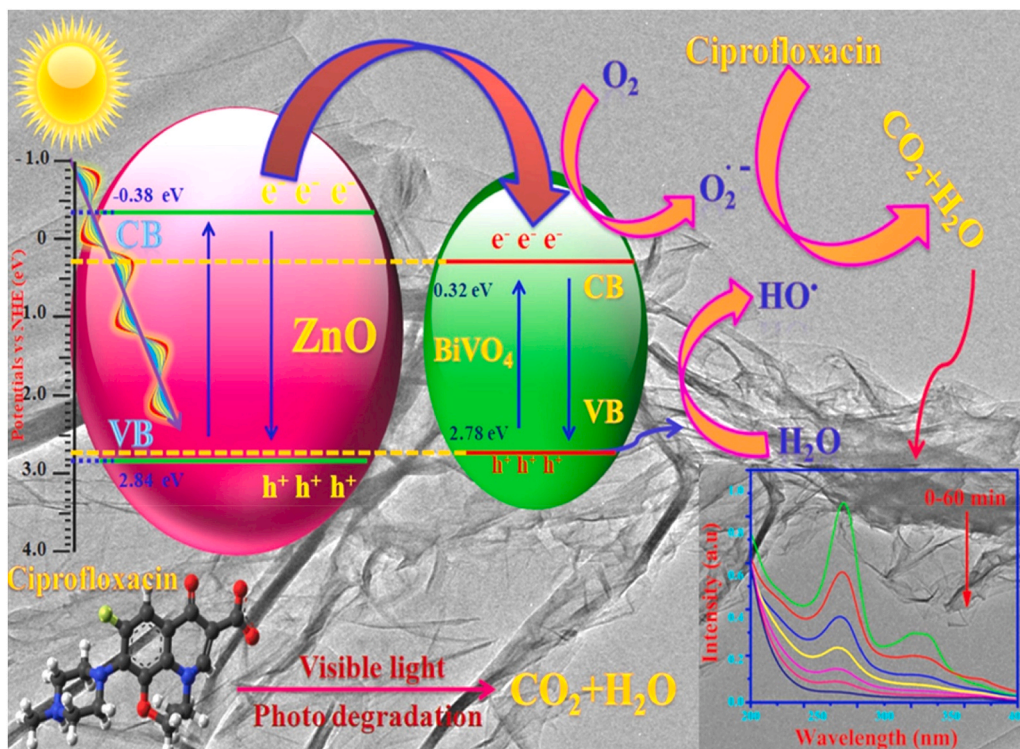


Fig. 13. Proposed pathway for the degradation of CIP utilizing the rGO-BiVO₄-ZnO nanocomposite, Reprinted with permission from (Raja et al., 2020), copyright 2022 Elsevier, License no. 5882910547472.

method for degradation of CIP using visible light (Gao et al., 2021). The produced nanocomposite exhibits homogeneous dispersion and an extensive surface area. The combination of Ce and rGO enhances the segregation of photo created charges, resulting in exceptional photocatalytic efficacy. The synthetic photocatalyst destroyed 94 % of ciprofloxacin underneath visible light illumination, markedly surpassing the 36 % degradation acquired by bare NiAlLDH. The incorporation of Ce and RGO enhances the separation of e⁻/h⁺ pair, leading to exceptional photocatalytic activity. Furthermore, the NiAlCeLDH/RGO exhibits remarkable cycling stability, retaining 84 % efficiency after five successive testing.

Table 8

Photocatalytic degradation of pesticides using graphene-based photocatalyst.

Pesticides	Catalyst	Energy Source	Operating Conditions	Photocatalytic Degradation (%)	References
Dimethoate	ZnO/rGO	UV light	[Dimethoate] ₀ = 5 mg/L, pH = 7, t = 180 min, Catalyst dosage = 0.5 g/L	99 %	(Zhu et al., 2020)
CP	g-C ₃ N ₄ /GO/V ₂ O ₅	Visible	[CP] ₀ = 100 mg/L, pH = 4.0, t = 120 min, Catalyst dosage = 0.3 g/L	88.97 %	(Tabasum et al., 2024)
CP	Cu-doped TiO ₂ /GO	UV light Visible light	[CP] ₀ = 100 mg/L, pH = 2.0, t = 80 min, Catalyst dosage = 0.2 g/L	91.4 % UV 78.25 % for visible	(Esfandian et al., 2024)
Acetamiprid	GO-CoFe ₂ O ₄	UV light	[Acetamiprid] ₀ = 16 mg/L, pH = 3.0, t = 60 min, Catalyst dosage = 0.1 g/L	97 %	(Tabasum et al., 2020)
CP	RMGO-Ag-V ₂ O ₅	Visible light	[CP] ₀ = 20 mg/L, pH = 7.0, t = 80 min, Catalyst dosage = 0.7 g/L	99 %	(Aziz et al., 2024)
CP	GNPs/ZrV ₂ O ₇	UV light Visible light	[CP] ₀ = 44.90 mg/L, pH = 4.05, t = 80 min, Catalyst dosage = 0.1 g/L	99.99 %	(Samy et al., 2020)
Atrazine	Graphene/g-C ₃ N ₄	Visible light	[Atrazine] ₀ = 10 mg/L, pH = 7, t = 300 min, Catalyst dosage = 0.3 g/L	100 %	(Altendji and Hamoudi, 2023)
Malathion Dichlorovos	GO-TiO ₂	UV light	[Malathion] ₀ = [Dichlorovos] ₀ = 0.5 mg/L, pH = 6, t = 80 min, Catalyst dosage = 0.06 g/L	Malathion = 90 % Dichlorovos = 80 %	(Kumar et al., 2022b)
CP	Graphene-CdS	Visible light	[CP] ₀ = 10 mg/L, pH = 7.5, t = 90 min, Catalyst dosage = 1.5 g/L	97.58 %	(Patel et al., 2024)
Diazinon	GO/Fe ₃ O ₄ /CeO ₂	Visible light	[Diazinon] ₀ = 30 mg/L, pH = 7.0, t = 60 min, Catalyst dosage = 0.2 g/L	97.9 %	(Naynava et al., 2024)

7.4. Degradation of pesticides

Pesticides are synthetic substances or combinations designed to prevent, eradicate, or control pests, including disease vectors, undesirable flora and fauna, and animals that inflict damage during the production, storage, distribution, transportation, or sale of food and agricultural products (Rasmussen et al., 2015). These pesticides demonstrate persistence, bioaccumulation, and ease of transfer, hence posing a significant hazard to environmental environments (Aziz et al., 2023). Chlorpyrifos (CP) is a very toxic organophosphate class utilized in agriculture for the eradication of rootworms, insects, and many undesirable weeds (Esfandian et al., 2024). The application of CP for food crops has been prohibited in the United States and Canada from 2000, subsequently in the United Kingdom from 2016, and in European countries from 2020 (Khan et al., 2018). Neonicotinoids represent a rapidly expanding category of commercial pesticides. They are derived from nicotine and function as substitutes for synthetic, highly hazardous insecticides (Hladik et al., 2018). The widespread application of these pesticides poses significant risks to both aquatic and terrestrial ecosystems. These substances are photo-stable, water-soluble, and resistant to biological destruction. Acetamiprid is a third-generation pesticide within this category and it is extensively utilized in diverse crops including leafy vegetables, melons, fruit trees, tobacco, wheat, and cotton to manage sucking insects such as beetles, aphids, and moths (Simon-Delso et al., 2015). It is soluble in numerous organic solvents and exhibits enhanced solubility in water (25 g/L), which elevates its concentration in surface water. Owing to its elevated water solubility, over 80 % of acetamiprid residues remained in the soil of treated crops, eventually infiltrating surface water or groundwater. A recent assessment across nine nations indicated that over 80 % of surface water contaminated with concentrations ranging from 0.14 to 18 $\mu\text{g/L}$. Research has shown that water arthropods and other aquatic plants and animals are not killed out at this concentration. Therefore, the concentration of pesticides in water must be diminished prior to its release into the environment. The studies of different authors that have utilized graphene-based composites as a photocatalyst for pesticide breakdown are detailed in this section (Table 8).

Zhu et al. (2020) have synthesized a ZnO/rGO nanocomposite through hydrothermal method and used it for dimethoate (DM) degradation using UV irradiation (Zhu et al., 2020). The photodegradation efficiency and degradation rate of DM by the ZnO/rGO nanocomposite were higher than 1.5 and 4 folds than ZnO. The pore volume and surface area of ZnO/rGO composite were $4.72 \times 10^{-3} \text{ cm}^3/\text{g}$ and $41.0 \text{ m}^2/\text{g}$ which were suitable for the mass transfer and adsorption of oxygen and pesticides. The greater photocatalytic effectiveness of the ZnO/rGO nanocomposite was attributed to the decreased e^-/h^+ recombination and improved carrier transport due to the presence of rGO. Photoelectrochemical tests verified that the nanocomposite demonstrated a high e^-/h^+ transfer rate at the composite interface. In another work, $\text{g-C}_3\text{N}_4/\text{GO}/\text{V}_2\text{O}_5$ nanocomposite was synthesized and utilized for the Chlorpyrifos (CP) degradation (Tabasum et al., 2024). The studies revealed that the $\text{g-C}_3\text{N}_4/\text{GO}/\text{V}_2\text{O}_5$ composite shown great degradation performance towards CP than $\text{g-C}_3\text{N}_4$. More than 88 % of CP has been degraded in just 120 min of irradiation. The used photocatalyst was regenerated with 0.1 g/10 mL of H_2O_2 solution and after five photocatalytic cycles the degradation efficiency is still 49.5 %. Esfandian et al. (2024) have synthesized a Cu-doped TiO_2/GO composite via situ chemical polymerization for the degradation of CP (Esfandian et al., 2024). The composite underneath UV light and visible light degrades 91.4 % and 78.25 % of CP respectively. The kinetic data

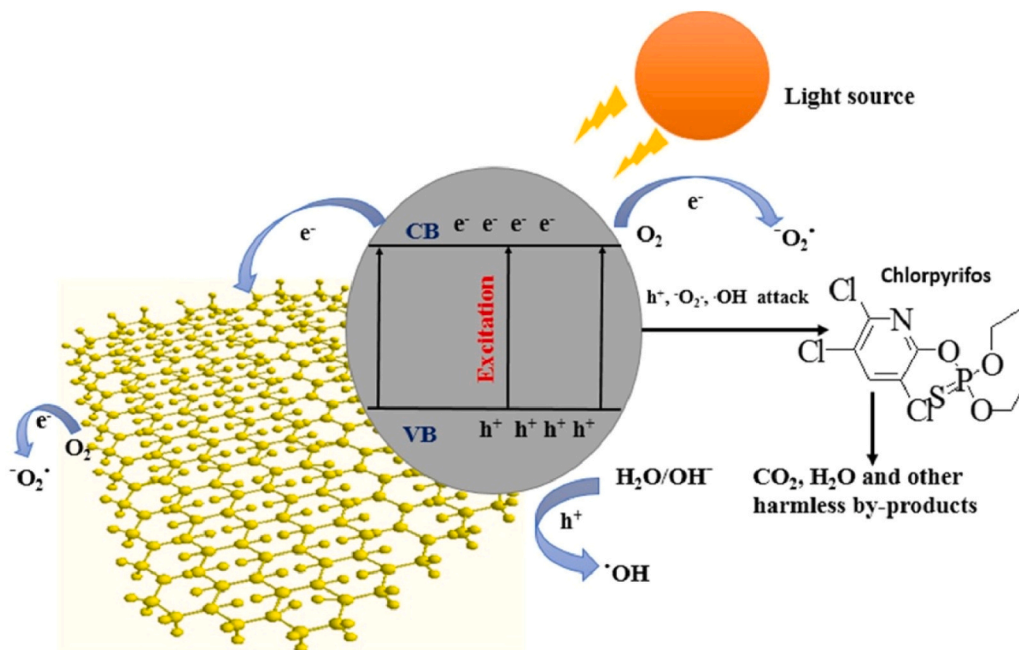


Fig. 14. The photocatalytic oxidation mechanism of CP by GNPs/ZrV₂O₇, Reprinted with permission from (Samy et al., 2020), copyright 2020 Elsevier, License no. 588291077030.

shows that Pseudo-first order model is the best fitted model with rate constant 0.0301 and 0.0177 min^{-1} with UV light and visible light respectively. The degradation mechanism involves the absorption of visible and UV light then e^- and h^+ generation after that e^- transfer, $OH^\bullet$ generation, pesticide degradation, and converted into harmless byproducts. A magnetic composite consists of cobalt ferrite decorated on graphene oxide (GO-CoFe₂O₄) was synthesized by ultrasonic impregnation using FeSO₄·7H₂O and FeCl₃·6H₂O as iron precursors (Fe²⁺ and Fe³⁺ respectively) (Tabasum et al., 2020). The synthesized GO-CoFe₂O₄ magnetic composite was used for acetamiprid degradation under UV light. The degradation study revealed that using GO-CoFe₂O₄ and GO-Fe₃O₄ nearly 97 and 90 % degradation of the acetamiprid occurred. The development of the composite boosted catalytic activity by preventing the aggregation of magnetite, thereby exposing active sites to both oxidants and contaminants in water. The scavenger study revealed that the $OH^\bullet$ radical mainly responsible for acetamiprid degradation. The optimized parameter conditions were catalyst dosage 0.1 g/L , pH 3, initial level 16 mg/L , and irradiation duration 60 min.

A novel composite consists of rGO with Ag/V₂O₅ as a composite was synthesized using hydrazine as a reducing agent for the degradation of CP and MO dye under visible light (Aziz et al., 2024). The kinetic study shows that the experimental results were best fitted by pseudo-first-order kinetics for both CP and MO with quantum yields of 2.16×10^{-3} and 1.07×10^{-3} molecules/photon and space time of 2.7×10^{-5} and 1.53×10^{-5} molecules/photon mg, respectively. From the scavenger study the results vouchsafed that the $OH^\bullet$ was the major contributor for the decomposition of both CP and MO. After 10 cycles of operation the catalyst still degrades more than 80 % which shows its remarkable commercial applications. Samy et al. (2020) have synthesized a low band-gap energy photocatalyst consists of graphene nano-platelets with zirconium vanadate (GNPs/ZrV₂O₇) for the degradation of CP (Samy et al., 2020). From the scavenger study it can be seen that without scavenger the degradation of CP was 96.8 %, where as in presence of OH^- , h^+ , and $\bullet O_2^-$ the degradation reduced to 64.8 %, 75.6 %, 95.2 %. After five consecutive degradation cycles the efficiency was still 91 % which indicates the photocatalyst stability. Fig. 14 shows the photocatalytic oxidation mechanism of CP by GNPs/ZrV₂O₇. An efficient graphene with graphitic carbon nitride (Graphene/g-C₃N₄) composite was produced through in situ method where g-C₃N₄ nanosheets were directly deposited on the graphene surface (Altendji and Hamoudi, 2023). The photocatalyst was used for the degradation of Atrazine a systemic herbicide used in weed control under visible light. The composite degrades 100 % of Atrazine in 5 h time whereas 40 % degradation occurs when the pristine g-C₃N₄ was used. This increase occurs due to the augmentation in adsorption sites on the surface of graphene for adsorption of Atrazine and also the easy transfer of (e^-/h^+) pairs on the surface of composite due to presence of graphene. After five cycles of degradation the graphene/g-C₃N₄ composite was still active for photocatalytic study which proved its stability and its commercial use in industrial scale. Kumar et al. (2022) have fabricated a heterogeneous photocatalyst using GO modified-TiO₂ (GO-TiO₂) nanocomposite for degradation of malathion and dichlorvos pesticides under UV and visible light (Kumar et al., 2022b). The outcomes revealed that the nanocomposite degrades 90 % and 80 % of malathion and dichlorvos, respectively. The kinetic study shown that the data followed Langmuir-Hinshelwood model. Malathion had a superior overall reaction rate in comparison to dichlorvos. The optimum parameter conditions were initial concentration 20 mg/L , pH 6, catalyst loading 60 mg/L , and irradiation duration 80 min.

7.5. Comparison of binary and ternary photocatalysts and semiconductor selection for Graphene derivatives

The efficiency of graphene-based photocatalysts for degrading organic pollutants is strongly dependent on the composite's structural composition, where binary and ternary composites play major roles with distinct characteristics and performance profiles (Thakur and Kandasubramanian, 2019). Binary composites, which consist of graphene derivatives such as graphene oxide (GO) or reduced graphene oxide (rGO) coupled with a single semiconductor photocatalyst (Suresh et al., 2020), have been vastly studied. Such composites typically demonstrate enhanced surface area, improved adsorption capacity, and more efficient charge carrier separation compared to bare semiconductor photocatalysts. For example, TiO₂/rGO and ZnO/GO composites have exhibited notable improvements in degrading various contaminants including dyes, pharmaceuticals, and pesticides (Ahtasham Iqbal et al., 2024; Zango et al., 2025). The high electron mobility of graphene derivatives facilitates faster electron transport and reduces electron-hole recombination (Shandilya et al., 2020), which is key to enhancing photocatalytic activity. However, binary composites often have intrinsic limitations such as relatively narrow visible light absorption and moderate charge carrier dynamics, which can limit their effectiveness in complex and diverse wastewater matrices.

In contrast, ternary composites incorporate two different semiconductor materials alongside graphene derivatives, leading to the formation of heterojunctions that considerably improve photocatalytic performance. These ternary systems, such as GO-ZnO/Mn₂O₃ (Rout et al., 2022), CeO₂/Fe₂O₃/rGO (Naidu, 2024), and g-C₃N₄/rGO/WO₃ (Lu et al., 2019), show superior degradation efficiencies compared to their binary counterparts. The synergistic interactions between multiple semiconductors optimize spatial charge separation by providing multiple pathways for photogenerated electrons and holes, thereby lowering recombination rates significantly (Raizada et al., 2019). Additionally, ternary composites broaden the light absorption range into the visible spectrum and increase the density of catalytic active sites, which together enhance overall photocatalytic efficiency (Jing et al., 2024). The effective interfacial charge transfers and trapping in these heterojunctions lead to their improved performance (Li et al., 2024). However, the synthesis of ternary composites is more complex and costly, and prolonged stability can be an issue, posing challenges for their large-scale application in wastewater treatment.

Selecting appropriate semiconductors for coupling with graphene derivatives is a critical factor that influences the photocatalyst's activity, stability, and suitability for specific pollutants. Semiconductors should possess compatible energy band positions and suitable band gap energies to form effective heterojunctions that facilitate charge carrier transfer. TiO₂ remains a popular choice because of its chemical stability, non-toxicity, and strong oxidative ability, though its wide band gap restricts visible light utilization (Pham and Thuy

Le, 2025); coupling with graphene derivatives helps to overcome this limitation by improving charge separation and extending light response. ZnO, with similar properties but higher electron mobility than TiO₂, has also been used successfully in both binary and ternary composites to enhance degradation efficiency (Zango et al., 2025). Metal oxides, like Mn₂O₃ (Rout et al., 2025), Fe₂O₃ (Samarasinghe et al., 2025), CeO₂ (Phor et al., 2025), and BiVO₄ (Liaqat et al., 2024) are often incorporated into ternary composites due to their narrower band gaps, adding visible light responsiveness and facilitating heterojunction formation for efficient charge separation. Graphitic carbon nitride (g-C₃N₄), a visible-light-active polymeric semiconductor, is frequently combined with graphene derivatives to further enhance photocatalytic performance (Priyadharshan et al., 2024). Transition metal sulfides (e.g., MoS₂, WS₂) and hybrid oxides offer additional catalytic synergies and visible light activity when integrated into graphene-based composites (Shinde et al., 2024; Tahir et al., 2023; Yu et al., 2021). In choosing semiconductors for graphene coupling, attention must be paid to the relative conduction and valence band edge positions to achieve favorable charge transfer mechanisms such as type-II or Z-scheme heterojunctions. These arrangements maximize electron-hole separation and reactive oxygen species production, which are essential for efficient photocatalytic degradation of pollutants. Thus, the semiconductor selection should be guided by a comprehensive understanding of band structure alignment, light absorption properties, and chemical stability under operational conditions.

Altogether, whilst binary graphene-semiconductor photocatalysts offer simplicity and notable photocatalytic enhancements, ternary composites offer superior performance due to synergistic effects between multiple semiconductors and graphene derivatives. Nonetheless, the design of ternary composites requires careful consideration of synthesis complexity, cost, and stability to enable practical applications. Strategic selection of semiconductor materials with appropriate band gaps, energy band alignment, and stability is fundamental for developing high-performance graphene-based photocatalysts. Future research should focus on rational design principles that integrate these factors to tailor efficient photocatalysts for targeted wastewater treatment challenges.

8. Challenges and future prospective

In this work, we give a wide-ranging review of the literature and the results of in-depth studies on the photocatalytic activity of nanocomposites based on graphene for use in wastewater treatment. According to the research, the photocatalytic efficacy in removing organic contaminants from wastewater is significantly enhanced when graphene is combined with metal semiconductors. The rise in the adsorption of organic contaminants on photocatalytic surfaces, along with improvements in visible light absorption and a decrease in photogenerated e^-/h^+ pair recombination, is responsible for this phenomenon. Despite all these advantages of graphene based photocatalysts some problems are still lies which needs to be addressed in the future:

- (i) Although graphene-based photocatalysts exhibit excellent pollutant degradation efficiency, their large-scale application remains limited by the complexity and expense of current production methods. High-quality techniques such as CVD are costly, while chemical oxidation–reduction routes introduce defects and raise environmental concerns. Recent efforts focus on green, low-cost synthesis approaches (e.g., plant extracts, biomass precursors) and scalable fabrication strategies to overcome these barriers. Advancing such sustainable methods is essential to make graphene-based photocatalysts practical for wastewater treatment
- (ii) Under visible light, graphene's photocatalytic potential is limited by its absence of a natural bandgap. Although techniques like heteroatom doping or heterostructure formation can assist adjust its electrical characteristics, these changes might make the synthesis more difficult and might not always result in the performance gains that are sought. Three-dimensional (3D) graphene structures are one example of a material design innovation that can increase electron transport characteristics and light absorption. These configurations could improve reactant interaction and boost photocatalytic reaction active sites. By combining graphene with other semiconductors or nanoparticles, hybrid systems may be produced that improve charge separation and catalytic efficiency overall by utilizing the advantages of each component. In the future, it will be essential to do research on band gap engineering and choose the best setups and combinations.
- (iii) The amalgamation of various materials with graphene to synthesize composite along with noble metal doping can enhance the degradation efficiency of the composite photocatalyst; however, it will increase the overall cost which results in the significant barrier to their widespread implementation in wastewater treatment.
- (iv) In the future, it is imperative to take into account how the synthesis and disposal of graphene-based materials may affect the environment. In order to support sustainable practices in photocatalytic applications, the production procedures should reduce waste and hazardous emissions. Future developments in this area will depend on creating more environmentally friendly synthesis methods that produce high-quality graphene products with the least possible impact on the environment. Methods like waste-derived precursors or bio-inspired approaches may provide sustainable substitutes.
- (v) Efforts should be made to use sun light as the energy source instead of UV or visible light, as solar light is a renewable energy and there will be no additional cost required.
- (vi) Future photocatalytic research should assess the efficacy of photocatalysts at pilot scales or inside real wastewater plant, rather than solely in laboratory settings. Furthermore, enhancing the recyclability and stability of composited substances in real exploitations is essential, owing to the intricacies of real wastewaters. Also, the importance of biological safety must also be underscored.
- (vii) For practical applications, it is crucial to sustain high activity while guaranteeing long-term durability. The inadequate stabilities and challenges in the reutilization of powdered size composites pose significant concerns for the real-world implementation of water remediation. Selecting adequate substrates for restraining photocatalyst materials or fabricating them in the

form of granular photocatalysts might diminish photocatalytic efficacy; however, materials exhibiting enhanced recyclability and greater stabilities are more ideal for practical exploitations.

- (viii) The scalability of graphene-based photocatalysts is limited by the complexity and expense of current production techniques. Techniques frequently call for exact control over the materials' composition and morphology, which can be difficult to reliably do. Research in the future should focus on overcoming the limitations of mass production of photocatalysts with desirable structure and morphology.
- (ix) Moreover, these photocatalysts must be fabricated as thin films to enhance their efficacy in degrading diverse industrial effluents laden with substantial quantities of various hazardous organic dyes, phenolic pollutants, pharmaceuticals, along with other deleterious substances.
- (x) The application of photocatalysis in conjunction with other AOPs presents a promising approach for the treatment of recalcitrant organic wastewater. Research should concentrate on examining the effects of reaction circumstances on the synergistic decomposition processes to enhance decomposition efficiency and maximize economic advantages.
- (xi) Despite the existing literature on the mechanism of photocatalytic degradation, it is essential to comprehend the fundamental relationships among the morphology, composition, structure, dimensions, and catalytic activity of photocatalysts.
- (xii) To effectively degrade various organic contaminants, it is essential to analyze the degradation mechanism in order to choose the most appropriate photocatalyst type. For instance, two charge types in dye molecules cause them to be present as cationic dye or anionic dye, which influence their sorption on the catalyst surface and therefore impact the efficacy of photocatalytic decomposition. Notwithstanding the previously described problems, graphene-based composite photocatalyst has limitless applications and potential in the treating of industrial wastewaters.
- (xiii) Since many photocatalyst systems (including graphene-based ones) tend to create a range of by-products instead of specified degradation products, achieving product selectivity throughout the degradation process can be considered as a valuable purpose in the future research efforts.

9. Conclusions

The current review work highlights the degradation of hazardous organic contaminants including dyes, phenolic pollutants, pharmaceuticals, and pesticides in wastewater, exploiting graphene-supported photocatalysts. Additionally, the principal reaction factors like solution pH, catalyst dosage, initial pollutant concentration, and irradiation time are also discussed. The kinetic data follows the Langmuir Hinshelwood model. The regeneration capacity of some photocatalysts has been examined, indicating that these photocatalysts can be utilized successfully without substantial degradation in their performance. The findings are highly encouraging in terms of degradation efficiency of organic pollutants. The review paper highlights the issues and challenges associated with the treatment of wastewater using graphene-supported photocatalysts. Also, perspectives for future research are outlined, and several recommendations are provided for comprehensive and accurate appraisal of photocatalytic systems. In summary, even though the development of graphene-based photocatalysts faces many challenges, continued studies into cutting-edge photocatalysts, production processes, and application strategies holds promise for overcoming these challenges and realizing the full potential of the graphene-based materials in sustainable environment remediation. At the end, it should be mentioned that, exploiting graphene-based materials as photocatalysts, interdisciplinary collaborations that integrate knowledge from chemistry, materials science, and engineering will promote creative answers to today's photocatalysis problems.

Author Contributions

"All authors contributed to the study conception and design. Data collection, analysis, and first draft of the manuscript was written by Dr. Dibya Ranjan Rout. Prof. Hara Mohan Jena, Prof. Aditya Kumar, and Prof. Ahmad Hosseini-Bandegharai commented on previous versions of the manuscript. All authors read and approved the final manuscript."

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Ahmad Hosseini-Bandegharai: Writing – review & editing, Writing – original draft, Supervision. **Omirsarik Baigenzhenov:** Writing – review & editing, Project administration, Methodology, Formal analysis. **Dibya Ranjan Rout:** Writing – original draft, Validation, Investigation, Formal analysis. **Aditya Kumar:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Hara Mohan Jena:** Writing – original draft, Validation, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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