

REVIEW ARTICLE

Photocatalytic nanomaterials for removing
emerging contaminants from water: Materials,
mechanisms, applications, and future directionsKien Vu*

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Abstract

Emerging contaminants, including pharmaceuticals, antibiotics, endocrine-disrupting chemicals, per- and polyfluoroalkyl substances (PFAS), pesticides, and personal care products, are increasingly detected in water sources and are difficult to remove using conventional wastewater treatment. Photocatalytic nanomaterials have emerged as a promising technology because they generate reactive oxygen species that can degrade or completely mineralize many persistent organic pollutants under light irradiation. This review summarizes recent advances in photocatalytic nanomaterials for water treatment, with a focus on titanium dioxide (TiO₂), zinc oxide (ZnO), graphitic carbon nitride (g-C₃N₄), metal-doped photocatalysts, and heterojunction nanocomposites. The basic principles of photocatalysis, the role of reactive oxygen species, and the main factors affecting photocatalytic performance are discussed. Recent applications for removing pharmaceuticals, antibiotics, PFAS, dyes, and endocrine-disrupting chemicals are also reviewed. Current challenges, including limited utilization of visible light, catalyst recovery, nanoparticle aggregation, photocorrosion, incomplete mineralization, and large-scale implementation, are critically discussed. Finally, future research directions, including solar-driven photocatalysis, photocatalytic membrane systems, multifunctional nanocomposites, artificial intelligence-assisted catalyst design, and life-cycle assessment, are highlighted. This review provides a concise overview of recent progress and identifies key research priorities for developing efficient and sustainable photocatalytic technologies for water treatment.

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1. Introduction

Clean water is essential for human health, ecosystems, agriculture, and economic development. However, rapid industrialization, urbanization, and agricultural activities have increased the release of harmful chemicals into aquatic environments. Despite major advances in wastewater treatment, trace organic contaminants are still frequently detected in rivers, lakes, groundwater, and even drinking water, creating a growing global environmental challenge.¹ Many of these pollutants, known as emerging contaminants, occur at very low concentrations but can still threaten human health and

ecosystems because they persist in the environment and are continuously released into water sources.

Emerging contaminants (ECs) include a wide range of chemicals, such as pharmaceuticals, antibiotics, personal care products, endocrine-disrupting chemicals (EDCs), pesticides, per- and polyfluoroalkyl substances (PFAS), industrial additives, and their transformation products. These contaminants originate from municipal wastewater, hospitals, pharmaceutical industries, agriculture, livestock production, and landfill leachate.² Many pharmaceuticals and antibiotics are only partially metabolized before being discharged into wastewater, while PFAS and pesticides enter water through industrial activities and agricultural runoff. Continuous release makes many ECs behave as persistent pollutants, even when they degrade slowly. Long-term exposure has been linked to endocrine disruption, reproductive and developmental disorders, ecological toxicity, and reduced aquatic biodiversity.³

Conventional wastewater treatment plants (WWTPs) are designed to remove solids, organic matter, nutrients, and pathogens, but they are often unable to remove ECs completely.⁴ Many of these contaminants resist biological degradation and remain in treated wastewater, allowing them to enter rivers, lakes, and coastal waters. In some cases, treatment also produces intermediate compounds that may be as harmful as, or even more harmful than, the original pollutants.

Among advanced treatment technologies, photocatalysis has emerged as a promising approach for removing persistent organic contaminants. When semiconductor materials absorb light, they generate reactive oxygen species (ROS), such as hydroxyl radicals ($\bullet\text{OH}$), superoxide radicals ($\text{O}_2^{\bullet-}$), and singlet oxygen, which can break down organic pollutants into smaller, less harmful compounds or completely mineralize them into carbon dioxide, water, and inorganic ions. Compared with conventional oxidation methods, photocatalysis operates under ambient conditions, requires fewer chemicals, can use solar energy, and has the potential to completely degrade pollutants rather than transfer them to another phase.⁵ Recent advances in nanotechnology have further improved photocatalytic performance. Nanomaterials such as titanium dioxide (TiO_2), zinc oxide (ZnO), graphitic carbon nitride ($\text{g-C}_3\text{N}_4$), metal-doped semiconductors, heterojunction photocatalysts, and composite materials provide larger surface areas, better charge separation, and expanded light absorption, resulting in higher degradation efficiency. Despite these advances, challenges such as limited utilization of visible light, rapid electron-hole recombination, photocorrosion, catalyst recovery, nanoparticle aggregation, and large-scale application

remain barriers to their practical use.⁶

Although several reviews have discussed photocatalysis or specific catalyst families separately, this review takes a more integrated approach by comparing the major photocatalytic nanomaterials used in water treatment— TiO_2 , ZnO , $\text{g-C}_3\text{N}_4$, metal-doped systems, and heterojunctions—within a single framework. The central question is how recent advances in material design, mechanism understanding, and application testing can be translated into more efficient, durable, and sustainable removal of emerging contaminants in water. To answer this question, the review synthesizes published studies on material properties, degradation mechanisms, contaminant classes, practical limitations, and future research priorities, with special attention to catalyst recovery, stability, reusability, and scale-up.

2. Emerging contaminants in aquatic environments

2.1. Sources of emerging contaminants

Emerging contaminants (ECs) are chemicals increasingly detected in rivers, lakes, groundwater, and drinking water but not fully regulated. Common ECs include pharmaceuticals, antibiotics, personal care products, endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), pesticides, dyes, and contaminants associated with microplastics. Although they are usually present at very low concentrations (in the range from ng/L to $\mu\text{g/L}$), they can persist in the environment because they are continuously released and are difficult to remove by conventional wastewater treatment.^{7,8}

ECs originate from many human activities and enter aquatic environments through different pathways (Figure 1). Hospitals discharge pharmaceuticals, antibiotics, disinfectants, and contrast media into municipal sewer systems. Domestic wastewater contains medicines, personal care products, cosmetics, detergents, and household chemicals released during daily activities. Agricultural runoff carries pesticides, herbicides, fertilizers, veterinary antibiotics, and livestock waste into nearby rivers and groundwater. Industrial facilities, including pharmaceutical, chemical, textile, and electronics industries, release PFAS, dyes, solvents, surfactants, and other specialty chemicals. Landfill leachate is another important source, containing pharmaceuticals, PFAS, plastic additives, and other persistent compounds that can contaminate groundwater and surface water if not properly managed.⁹

Although wastewater treatment plants (WWTPs) remove many conventional pollutants, they are not

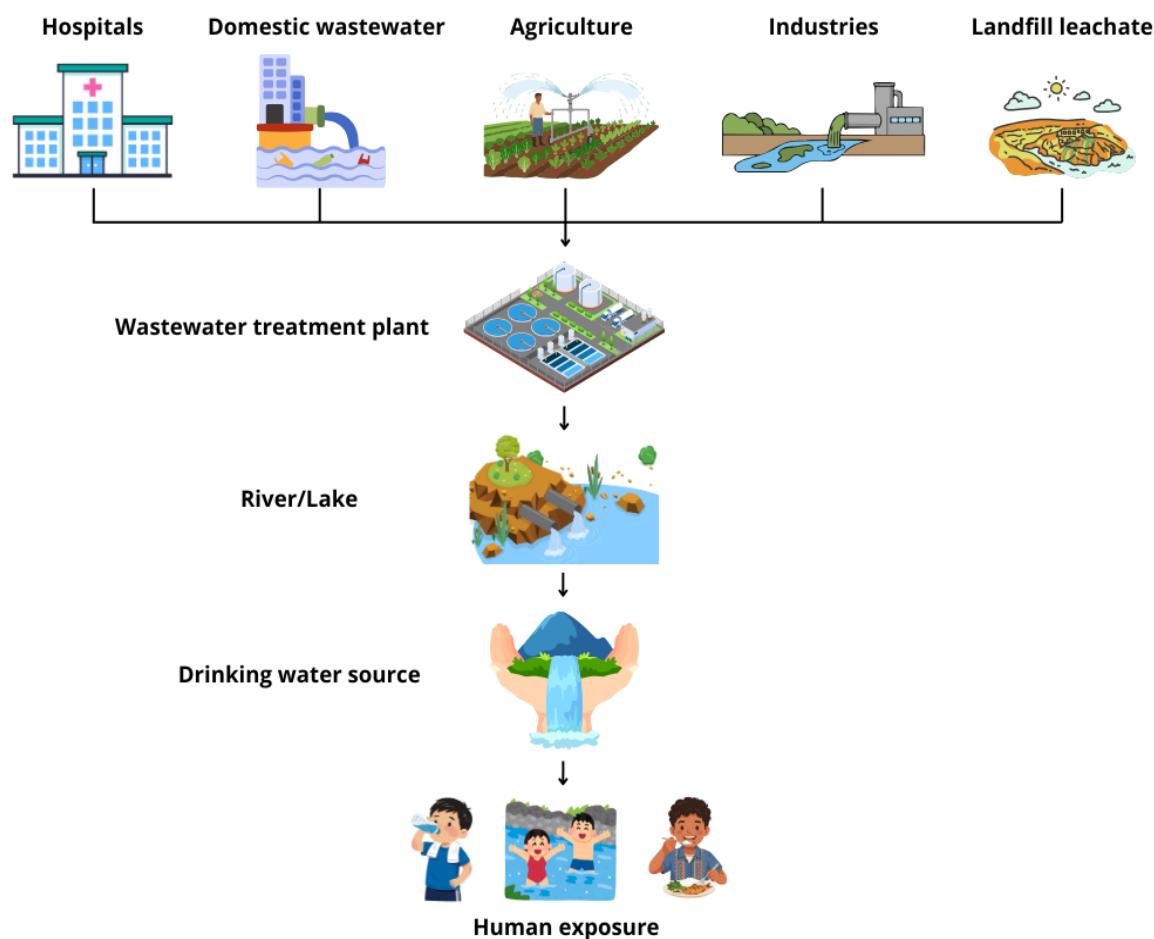


Figure 1. Pathway of emerging contaminants in aquatic environments

designed to eliminate ECs completely. As a result, many contaminants remain in treated wastewater and are discharged into rivers, lakes, and coastal waters. Because these water bodies are often used as drinking water sources, ECs can eventually enter drinking water supplies, leading to long-term human exposure.

2.2. Environmental impacts

Although ECs are usually present at low concentrations, their continuous release can have significant effects on ecosystems and human health. Pharmaceuticals, pesticides, and industrial chemicals can be toxic to fish, algae, aquatic invertebrates, and beneficial microorganisms.¹⁰ Hormones and endocrine-disrupting chemicals can interfere with normal hormone function, leading to reproductive problems, developmental abnormalities, and reduced fertility in aquatic organisms. In addition, the continuous release of antibiotics promotes the spread of antibiotic-resistant bacteria and antibiotic resistance genes (ARGs),

creating a growing public health concern.^{11,12} Many ECs, especially PFAS, are highly persistent and can accumulate in water, sediments, and living organisms. Microplastics can also adsorb and transport ECs, thereby spreading them through aquatic ecosystems. These challenges highlight the need for advanced treatment technologies that can effectively remove or completely degrade emerging contaminants before they reach natural waters and drinking water supplies.

3. Fundamentals of photocatalytic degradation

Photocatalysis is an advanced oxidation process (AOP) that uses light and semiconductor materials to break down organic pollutants into less harmful compounds. Unlike conventional treatment methods that only transfer pollutants from one phase to another, photocatalysis can destroy them through oxidation reactions on the

catalyst surface. Because it can use solar energy, requires few chemicals, and produces little secondary pollution, photocatalysis has become a promising technology for sustainable water treatment.

3.1. Light absorption and charge separation

Photocatalysis begins when a semiconductor such as titanium dioxide (TiO_2) absorbs photons with energy equal to or greater than its band gap, which excites electrons from the valence band to the conduction band and leaves positive holes behind. The photogenerated electrons and holes migrate to the catalyst surface, where electrons reduce dissolved oxygen to superoxide radicals ($\text{O}_2^{\bullet-}$) and holes oxidize water or hydroxide ions to hydroxyl radicals ($\bullet\text{OH}$). These reactive species attack pollutant molecules through oxidation, bond cleavage, and stepwise transformation into smaller intermediates, and under suitable conditions the reaction can proceed to complete mineralization into carbon dioxide, water, and inorganic ions. The efficiency of this process depends on how effectively charge carriers are separated and transferred to the surface before recombination occurs, which is why surface defects, cocatalysts, and heterojunctions are so important in photocatalyst design. The overall process is illustrated in Figure 2. The major reactions involved in TiO_2 photocatalysis are:



The efficiency of photocatalysis depends on how well the electron-hole pairs remain separated. If they recombine before reaching the catalyst surface, the absorbed light energy is lost as heat and the degradation efficiency decreases.¹³ To reduce recombination, researchers have developed metal-doped photocatalysts, heterojunctions, and other nanostructured materials that improve charge separation.

3.2. Reactive oxygen species

Reactive oxygen species (ROS) are the primary oxidizing agents responsible for pollutant degradation during photocatalysis. The three most important ROS are hydroxyl radicals ($\bullet\text{OH}$), superoxide radicals ($\text{O}_2^{\bullet-}$), and singlet oxygen ($^1\text{O}_2$).

Hydroxyl radicals ($\bullet\text{OH}$) are the strongest oxidizing species and can rapidly degrade many organic pollutants

through oxidation reactions, eventually converting them into harmless products.¹⁴ Superoxide radicals ($\text{O}_2^{\bullet-}$) are formed when photogenerated electrons react with dissolved oxygen. Although they are less reactive than hydroxyl radicals, they help initiate degradation and generate additional ROS, such as hydrogen peroxide.¹⁵ Singlet oxygen ($^1\text{O}_2$) also contributes to pollutant removal, especially in modified photocatalytic systems, and is effective for degrading pharmaceuticals, dyes, and other persistent organic compounds.¹⁶ Together, these ROS enable photocatalysis to remove a wide range of emerging contaminants.

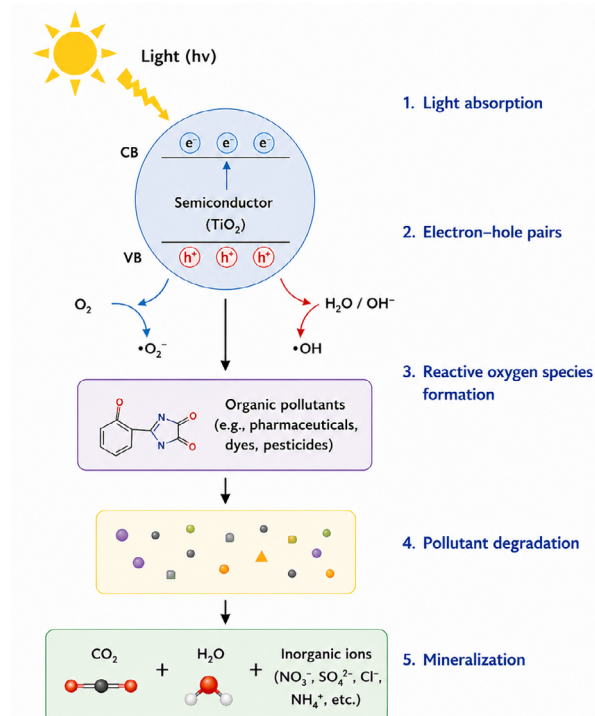


Figure 2. Basic mechanism of photocatalytic degradation of organic pollutants

3.3. Factors affecting photocatalytic performance

The performance of photocatalytic systems is influenced by several operating parameters that affect pollutant adsorption, ROS production, and degradation kinetics. Solution pH affects both the surface charge of the photocatalyst and the chemical speciation of contaminants.⁵ Depending on the pollutant, acidic or alkaline conditions may enhance adsorption and improve degradation efficiency. Catalyst dosage determines the number of available active sites. Increasing catalyst loading generally improves degradation until an optimum dosage is reached.¹⁷ Excessive catalyst concentrations can reduce light penetration due to particle aggregation and light scattering. Pollutant concentration influences reaction kinetics. At low concentrations,

contaminants are readily degraded because there are sufficient reactive sites available. At higher concentrations, pollutants compete for active sites and ROS, leading to slower degradation rates.¹⁸ Light intensity directly affects electron-hole generation. Higher light intensity generally increases ROS production and photocatalytic activity until saturation occurs, beyond which additional light produces only limited improvements.¹⁹ Dissolved oxygen serves as an electron acceptor, reducing electron-hole recombination and promoting the formation of superoxide radical.²⁰ Insufficient dissolved oxygen decreases ROS generation and lowers photocatalytic performance (Table 1). Understanding these basic principles is important for developing more efficient photocatalytic nanomaterials and improving their application in water treatment. Better catalyst design and optimized operating conditions can increase pollutant removal efficiency and support the practical use of photocatalysis for treating emerging contaminants.

Table 1. Major factors affecting photocatalytic degradation

Factor	Role	Typical operating range	Ref.
pH	Affects the catalyst surface and pollutant adsorption	3–9 (many TiO ₂ systems perform best around 5–7)	21
Catalyst dosage	Determines the number of active sites	0.1–2.0 g/L	22
Pollutant concentration	Influences the degradation rate	1–100 mg/L in laboratory studies (often much lower in real wastewater)	23
Light intensity	Produces electron-hole pairs and ROS	10–100 mW/cm ² (UV or simulated solar light)	24
Dissolved oxygen	Promotes ROS formation	5–9 mg/L (oxygen-saturated water at room temperature)	25

Notes: Typical values reported in photocatalytic studies. The optimum conditions depend on the photocatalyst, pollutant type, reactor design, and water quality.

Abbreviations: ROS: Reactive oxygen species; UV: Ultraviolet.

4. Photocatalytic nanomaterials

The performance of photocatalysis depends not only on the semiconductor composition but also on crystallinity, phase composition, particle size, morphology, porosity, defect density, and surface chemistry. In the literature, these features are commonly characterized using X-ray diffraction (XRD), scanning and transmission electron microscopy (SEM/TEM), Brunauer–Emmett–Teller (BET) surface area analysis, UV-Vis diffuse reflectance

spectroscopy, photoluminescence (PL), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and X-ray photoelectron spectroscopy (XPS). These data help explain why two materials with the same base composition may show different photocatalytic performance. Because this review synthesizes published studies rather than reporting new experiments, the discussion below emphasizes structure-property relationships reported in the literature and how they are linked to pollutant removal efficiency.

4.1. Titanium dioxide-based nanomaterials

Titanium dioxide (TiO₂) is the most widely studied photocatalyst for water treatment because it is chemically stable, non-toxic, inexpensive, and corrosion-resistant.²⁶ It exists in three main crystal forms, anatase, rutile, and brookite, with anatase generally showing the highest photocatalytic activity. TiO₂ has been successfully used to remove pharmaceuticals, antibiotics, dyes, pesticides, EDCs, and other organic contaminants.

TiO₂ nanoparticles are the most common form because they provide a large surface area and many active sites for pollutant adsorption and ROS generation. They are easy to synthesize using methods such as sol-gel, hydrothermal, and precipitation.²⁷ However, TiO₂ mainly absorbs ultraviolet (UV) light because of its wide band gap (about 3.2 eV), and UV accounts for only about 5% of sunlight.²⁸ In addition, nanoparticles are difficult to recover from treated water and tend to aggregate during repeated use.

TiO₂ nanotubes have a one-dimensional tubular structure that improves electron transport and reduces electron-hole recombination. They also provide better mechanical stability and are suitable for photocatalytic membranes and continuous-flow treatment systems.²⁹ However, their preparation is more complex and usually involves anodization or hydrothermal synthesis.

TiO₂ nanofibers are commonly produced by electrospinning followed by heat treatment.³⁰ Their fibrous structure makes them easy to separate from water and reuse, reducing catalyst loss. Although they sometimes have a lower surface area than nanoparticles, they are more practical for membrane reactors and fixed-bed systems because catalyst recovery is much easier.

To overcome the limitations of conventional TiO₂, researchers have developed several modification strategies, including metal and non-metal doping, oxygen vacancy engineering, heterojunction construction, and coupling with carbon materials. TiO₂ has also been combined with membranes, activated carbon, graphene oxide, and biochar to improve pollutant adsorption, visible-light activity, and catalyst recovery.^{31,32} Despite these improvements, limited

visible-light utilization and large-scale application remain important challenges.

4.2. Zinc oxide

Zinc oxide (ZnO) is another widely studied photocatalyst with properties similar to TiO_2 . It is inexpensive, easy to synthesize, has high electron mobility, and shows strong photocatalytic activity under UV light.³³ Compared with TiO_2 , ZnO often provides faster electron transport and higher degradation rates for dyes and some pharmaceutical compounds. The main limitation of ZnO is its lower chemical stability. It can undergo photocorrosion during long-term irradiation and dissolves more easily under acidic conditions, reducing its performance.³⁴ Like TiO_2 , ZnO mainly absorbs UV light. To improve its efficiency, ZnO is often combined with carbon materials, metal nanoparticles, or other semiconductors to reduce photocorrosion and enhance visible-light absorption.

4.3. Graphitic carbon nitride

Graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) is one of the most promising metal-free photocatalysts because it can absorb visible light. Its narrower band gap (about 2.7 eV) allows better use of solar energy than TiO_2 or ZnO.³⁵ It is also inexpensive and can be prepared from nitrogen-rich precursors such as melamine, urea, and dicyandiamide. $\text{g-C}_3\text{N}_4$ has shown good performance for removing pharmaceuticals, antibiotics, dyes, and EDCs under visible light. However, pure $\text{g-C}_3\text{N}_4$ has low electrical conductivity and rapid electron-hole recombination, which limit its

efficiency. To overcome these limitations, it is commonly modified through porous structure design, exfoliation, metal doping, or coupling with TiO_2 , ZnO, carbon materials, and metal-organic frameworks (MOFs).³⁶

4.4. Metal-doped photocatalysts

Metal doping is an effective way to improve photocatalytic performance. Metal ions create new energy levels within the semiconductor, improve visible-light absorption, and reduce electron-hole recombination. Silver (Ag) is widely used because it enhances electron transfer and visible-light absorption, making Ag- TiO_2 highly effective for degrading pharmaceuticals and antibiotics. Iron (Fe) improves charge separation and promotes hydroxyl radical production through Fenton-like reactions, while copper (Cu) increases visible-light absorption by narrowing the band gap. Cobalt (Co) also improves charge separation and has shown promising results for antibiotic degradation. However, excessive metal loading can reduce photocatalytic activity by creating recombination centers, so the dopant concentration must be carefully optimized.³⁷

4.5. Heterojunction photocatalysts

Heterojunction photocatalysts combine two or more semiconductors to improve charge separation and increase photocatalytic efficiency. This reduces electron-hole recombination and enhances ROS production. One of the best-known examples is the $\text{TiO}_2/\text{g-C}_3\text{N}_4$ heterojunction, which combines the stability of TiO_2 with the visible-light activity of $\text{g-C}_3\text{N}_4$ (Table 2). This combination has shown

Table 2. Comparison of common photocatalytic nanomaterials for emerging contaminant removal

Material	Typical pollutants	Removal performance	Advantages	Limitations	Ref.
TiO_2	Pharmaceuticals, antibiotics, dyes	80%–99%	Stable, non-toxic, low cost	Mainly active under UV light	38
ZnO	Dyes, pesticides	75%–98%	Low cost, high electron mobility	Photocorrosion Limited stability in acidic water	39
$\text{g-C}_3\text{N}_4$	Pharmaceuticals, EDCs	70%–95%	Visible-light active, metal-free	Low conductivity Rapid charge recombination	40
Ag- TiO_2	Antibiotics, pharmaceuticals	90%–99%	Better visible-light absorption and charge separation	High material cost	41
Heterojunction photocatalysts	Mixed emerging contaminants	90%–99%	High photocatalytic efficiency Effective charge separation	More complex synthesis	42

Notes: Typical removal efficiencies reported in laboratory studies. Actual performance depends on the photocatalyst, pollutant type and concentration, light source, reaction time, pH, and operating conditions.

Abbreviation: EDC: Endocrine-disrupting chemical; UV: Ultraviolet.

excellent performance for removing pharmaceuticals, antibiotics, and EDCs.⁴³ Another widely studied system is ZnO/TiO₂, in which ZnO enhances electron transport while TiO₂ increases stability and reduces photocorrosion.⁴⁴

More recently, researchers have explored MOF-based composites. Because metal-organic frameworks have high surface areas and porous structures, they can adsorb pollutants before photocatalytic degradation. Combining MOFs with TiO₂, ZnO, or g-C₃N₄ improves adsorption, charge separation, and overall photocatalytic performance, making these composites promising for future water treatment applications.

Across the reviewed studies, TiO₂ remains the benchmark catalyst because of its stability, low cost, and low toxicity, but it is usually constrained by UV-only activation. ZnO can show faster electron transport and high activity, yet it is more vulnerable to photocorrosion. g-C₃N₄ offers visible-light response and metal-free chemistry, but its limited conductivity and rapid charge recombination often restrict performance. Metal doping and heterojunction construction typically improve light harvesting and charge separation, but they can also increase synthesis complexity, cost, and uncertainty in large-scale deployment. Reported differences in removal efficiency often reflect variations in light source, pH, catalyst dosage, pollutant concentration, water matrix composition, and reactor configuration, so direct comparisons across studies should be interpreted cautiously.

5. Applications in water treatment

Photocatalytic nanomaterials have been widely studied for removing ECs from water. Under light irradiation, they produce ROS that break down persistent organic pollutants into smaller, less harmful compounds. Unlike adsorption, which only transfers pollutants from water to a solid material, photocatalysis can completely mineralize many organic contaminants into carbon dioxide, water, and inorganic ions.

5.1. Pharmaceuticals

Pharmaceuticals are among the most common emerging contaminants found in surface water, groundwater, and treated wastewater because many drugs are only partly metabolized in the human body and are not completely removed by conventional wastewater treatment. Their continuous release has raised concerns about ecological toxicity and long-term environmental impacts. Several pharmaceuticals are commonly used to evaluate photocatalytic performance. Ibuprofen can be effectively degraded by TiO₂- and ZnO-based photocatalysts under UV light via hydroxylation, ring opening, and

mineralization.⁴⁵ Diclofenac, one of the most persistent pharmaceuticals, can be removed more efficiently using TiO₂/g-C₃N₄ heterojunctions and Ag-doped TiO₂ under visible light, as these materials enhance charge separation and ROS production.⁴⁶ Sulfamethoxazole has also been successfully degraded using metal-doped photocatalysts and heterojunctions, often with higher mineralization than pure TiO₂.⁴⁷ For carbamazepine, g-C₃N₄-based composites and TiO₂ heterojunctions have shown promising results under simulated solar light, although complete mineralization remains difficult because stable intermediate products can still form.³³

5.2. Per- and polyfluoroalkyl substances

Per- and polyfluoroalkyl substances (PFAS) are among the most difficult contaminants to remove because of the strong carbon-fluorine (C-F) bond. Conventional biological treatment and many oxidation processes are generally ineffective, while adsorption only transfers PFAS from water to a solid phase.⁴⁸ Photocatalysis has emerged as a promising approach because it can gradually break C-F bonds and promote defluorination.⁴⁹ Modified TiO₂, bismuth-based photocatalysts, photocatalytic membranes, and carbon-supported composites have shown improved PFAS degradation. However, PFAS remain more difficult to degrade than pharmaceuticals or dyes, especially short-chain PFAS, which are more resistant.⁵⁰ Combining photocatalysis with adsorption, electrochemical oxidation, or persulfate activation is expected to improve treatment efficiency further.

5.3. Antibiotics

Antibiotics are a major environmental concern because they contribute to ecological toxicity and the spread of antimicrobial resistance. Photocatalysis has shown high removal efficiency for antibiotics such as tetracycline, ciprofloxacin, sulfamethoxazole, amoxicillin, and chloramphenicol.⁵¹ During the process, ROS attack the molecular structure of antibiotics, leading to degradation and eventual mineralization. In addition to removing antibiotics, photocatalysis can reduce their biological activity and help limit the spread of antibiotic-resistant bacteria. Recent studies have also reported the degradation of ARGs, although complete removal remains challenging.⁵² Therefore, future studies should evaluate both contaminant removal and ARG reduction.

5.4. Dyes

Synthetic dyes are widely used as model pollutants because they are easy to detect and chemically stable. Textile wastewater often contains dyes that reduce light penetration and may be toxic to aquatic organisms. Photocatalysis

is highly effective for degrading dyes such as methylene blue, rhodamine B, methyl orange, and malachite green.⁵³ ROS rapidly break down the dye molecules, leading to decolorization and subsequent mineralization into carbon dioxide and water (Figure 3). Although dye removal is often easier than pharmaceutical or PFAS degradation, dyes are mainly used as model pollutants. Future studies should increasingly test photocatalysts using real wastewater containing mixtures of contaminants.

5.5. Endocrine-disrupting chemicals

Endocrine-disrupting chemicals (EDCs), such as bisphenol A (BPA), estradiol, estrone, and nonylphenol, can interfere with hormone systems even at very low concentrations. Their persistence and biological activity make them important targets for advanced water treatment.

TiO₂, ZnO, and g-C₃N₄-based photocatalysts have shown high removal efficiencies for BPA and other EDCs under UV or simulated solar light.^{54,55} However, some intermediate products formed during degradation may still have endocrine-disrupting activity. Therefore, future research should evaluate both contaminant removal and toxicity reduction (Table 3).

Photocatalytic degradation studies are commonly interpreted using pseudo-first-order kinetics under dilute conditions, often within the Langmuir–Hinshelwood framework; zero-order or second-order behavior may also appear when adsorption, mass transfer, or surface saturation becomes important. Kinetic fitting is useful for comparing catalysts, but it should be interpreted together with mineralization, toxicity, stability, and reuse

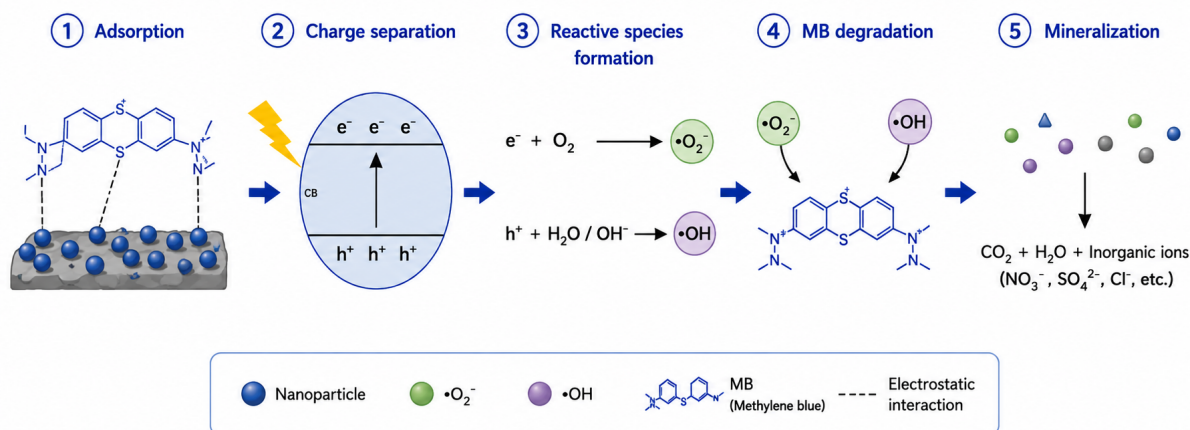


Figure 3. Photocatalytic degradation of methylene blue (MB) using a nanoparticle-based photocatalyst

Table 3. Representative applications of photocatalytic nanomaterials for removing emerging contaminants

Pollutant	Representative catalyst	Removal performance	Light source	Ref.
Ibuprofen	TiO ₂ nanoparticles	85%–98%	UV	56
Diclofenac	TiO ₂ /g-C ₃ N ₄ heterojunction	90%–99%	Visible light	43
Sulfamethoxazole	Ag-TiO ₂	90%–99%	Visible light	57
Carbamazepine	g-C ₃ N ₄ composite	80%–95%	Simulated solar light	58
PFAS (PFOA/PFOS)	Modified TiO ₂ composite	40%–90%	UV	59
Tetracycline	Fe- or Co-doped photocatalyst	90%–99%	Visible light	60
Methylene blue	ZnO nanoparticles	>95%	UV	61
Bisphenol A	TiO ₂ /g-C ₃ N ₄ heterojunction	90%–99%	Visible light	62

Notes: Removal efficiencies are typical values reported in laboratory studies. Actual performance depends on the photocatalyst, pollutant type and concentration, light source, reaction time, pH, and operating conditions.

Abbreviations: PFAS: Per- and polyfluoroalkyl substances; PFOA: Perfluorooctanoic acid; PFOS: Perfluorooctanesulfonic acid; UV: Ultraviolet.

data. Regeneration is especially important for practical application, and immobilized, membrane-supported, and magnetic photocatalysts generally offer better recoverability than suspended powders, although activity loss can still occur through fouling, aggregation, or photocorrosion during repeated cycles.

Overall, photocatalytic nanomaterials demonstrated excellent performance in removing a range of emerging contaminants, particularly pharmaceuticals, antibiotics, dyes, and endocrine-disrupting chemicals. PFAS remain the most difficult pollutants because of their strong carbon-fluorine bonds. Continued improvements in catalyst design, heterojunction engineering, and hybrid treatment systems are expected to make photocatalytic technologies more effective for practical water treatment.

6. Current challenges

Although photocatalytic nanomaterials have shown great potential for removing emerging contaminants from water, several challenges still limit their large-scale application. Most studies have been carried out under controlled laboratory conditions, and achieving similar performance in real wastewater treatment systems remains difficult.

One of the main limitations is the poor use of visible light. Titanium dioxide (TiO_2), the most widely used photocatalyst, has a band gap of about 3.2 eV and is mainly activated by UV light, which makes up only about 5% of sunlight.⁶³ Although metal doping, heterojunctions, and $\text{g-C}_3\text{N}_4$ -based composites have improved visible-light absorption, many photocatalysts still show lower efficiency under natural sunlight than under laboratory light sources.

Another challenge is catalyst recovery. Most photocatalysts are used as fine powders suspended in water, making them difficult to separate after treatment. Poor recovery increases operating costs and may lead to secondary nanoparticle pollution. To address this problem, researchers have developed photocatalysts supported on membranes, glass, ceramics, activated carbon, and magnetic materials. While these approaches make catalyst recovery easier, they may also reduce the available surface area and lower photocatalytic activity.

Nanoparticle aggregation is another common problem. In real wastewater, dissolved salts, natural organic matter, and suspended solids can cause nanoparticles to clump, reducing their active surface area and limiting light penetration.⁶⁴ Surface modification, carbon supports, and polymer coatings have been used to improve particle stability, but maintaining long-term performance remains challenging.

Photocorrosion also limits the lifetime of some

photocatalysts. Materials such as ZnO and several metal sulfides gradually lose activity during repeated use because their structures degrade under light irradiation.⁶⁵ Although TiO_2 is more stable, many visible-light photocatalysts are less durable. Developing materials that combine high activity with long-term stability is therefore an important research goal.

Another concern is the formation of intermediate products. Although photocatalysis can completely mineralize some pollutants, persistent compounds such as PFAS and certain pharmaceuticals are often only partly degraded. Some intermediate products may be as toxic as, or even more toxic than, the original contaminants. Therefore, evaluating photocatalytic performance should include not only pollutant removal but also mineralization efficiency and toxicity assessment.

Overall, the literature reviewed here is dominated by bench-scale experiments and synthetic water matrices, which limits direct comparison across studies and makes translation to full-scale treatment more uncertain. At the same time, one strength of this review is that it integrates multiple photocatalyst families, pollutant classes, and implementation issues into a single framework, helping to identify the common technical bottlenecks that must be addressed before large-scale deployment.

Scaling up photocatalytic technologies is another major challenge. Most laboratory studies use synthetic wastewater with a single pollutant, whereas real wastewater contains mixtures of organic matter, inorganic ions, suspended solids, and multiple contaminants that compete for reactive oxygen species and active sites. In addition, full-scale systems must address practical issues, including reactor design, light distribution, catalyst immobilization, energy consumption, and long-term operation. More pilot-scale studies using real wastewater are needed before these technologies can be widely applied.

Finally, cost remains an important barrier. Although TiO_2 is relatively inexpensive, advanced photocatalysts containing metal dopants, heterojunctions, or complex nanostructures are often more expensive to produce. Additional costs arise from reactor construction, artificial light sources, catalyst recovery, and system maintenance. Future research should focus on developing photocatalysts that are efficient, durable, easy to recover, and cost-effective for large-scale water treatment.

7. Future perspectives

Photocatalytic nanomaterials have shown great potential for removing emerging contaminants from water. However, most studies have been conducted at the laboratory scale.

Future research should focus on developing technologies that are more efficient, cost-effective, and suitable for large-scale water treatment.

One important direction is the development of solar-driven photocatalysis. Because sunlight is abundant and free, photocatalysts that efficiently utilize visible light could reduce energy consumption and operating costs. Future materials should be designed to absorb more sunlight and improve charge separation under natural conditions. Another promising approach is the use of photocatalytic membrane systems. Immobilizing photocatalysts on membrane surfaces combines filtration and photocatalytic degradation in a single process. This approach can improve contaminant removal, reduce membrane fouling, simplify catalyst recovery, and support continuous water treatment.

Magnetic photocatalysts also offer a practical solution for catalyst recovery. By incorporating magnetic materials such as Fe_3O_4 , photocatalysts can be easily separated from treated water using an external magnetic field. This reduces catalyst loss, lowers operating costs, and minimizes the release of nanoparticles into the environment.

Future studies should also focus on multifunctional nanocomposites that combine photocatalysis with adsorption. Materials containing activated carbon, biochar, or MOFs can first concentrate pollutants near the catalyst surface and then degrade them more efficiently. These hybrid materials are particularly promising for treating persistent contaminants such as PFAS and pharmaceuticals.

Artificial intelligence (AI) and machine learning are expected to play an increasingly important role in photocatalyst design. These tools can analyze large datasets to identify relationships between catalyst composition, structure, and performance, helping researchers develop more effective photocatalysts while reducing the time and cost of material development.

More research is also needed under real operating conditions. Most current studies use synthetic wastewater containing a single pollutant, whereas real wastewater contains complex mixtures of contaminants, dissolved organic matter, and inorganic ions. Pilot-scale studies using real wastewater are needed to evaluate long-term catalyst stability, mineralization efficiency, and overall treatment performance.

Emerging contaminants, including pharmaceuticals, antibiotics, PFAS, endocrine-disrupting chemicals, pesticides, and personal care products, are increasingly found in water sources and are difficult to remove using conventional wastewater treatment. Photocatalytic nanomaterials have emerged as a promising solution because they generate ROS that can break down or

completely mineralize many persistent pollutants under light irradiation. Across the reviewed studies, representative laboratory removal efficiencies were often about 80%–99% for TiO_2 -based systems, 75%–98% for ZnO , 70%–95% for $\text{g-C}_3\text{N}_4$, 90%–99% for Ag-doped TiO_2 and other heterojunctions, and 40%–90% for PFAS depending on catalyst type and operating conditions. Among the photocatalysts reviewed, TiO_2 remains the benchmark because it is stable, non-toxic, and inexpensive, while ZnO , $\text{g-C}_3\text{N}_4$, metal-doped photocatalysts, and heterojunction nanocomposites offer improvements in visible-light response, charge separation, and pollutant degradation.

This review is limited by the heterogeneity of the published literature, the predominance of laboratory-scale experiments, and the difficulty of directly comparing studies that use different light sources, water matrices, pollutant concentrations, and reactor designs. A major strength of the review is that it integrates multiple photocatalyst families, contaminant classes, and practical implementation issues in one coherent framework, which helps identify the technical bottlenecks that must be addressed before large-scale application.

Future research should focus on developing practical and sustainable treatment technologies rather than increasingly complex materials. Promising directions include solar-driven photocatalysis, photocatalytic membrane systems, magnetic and multifunctional photocatalysts, hybrid adsorption-photocatalysis processes, and AI-assisted catalyst design. More pilot-scale studies using real wastewater, together with life-cycle assessment (LCA) and techno-economic analysis (TEA), are also needed to evaluate feasibility, environmental impacts, and treatment costs. Overall, advances in material design, reactor development, and sustainability assessment will help move photocatalytic nanomaterials from laboratory research to practical and sustainable water treatment.

8. Conclusions

Emerging contaminants, including pharmaceuticals, antibiotics, PFAS, endocrine-disrupting chemicals, pesticides, and personal care products, are increasingly found in water sources and are difficult to remove using conventional wastewater treatment. Photocatalytic nanomaterials have emerged as a promising solution because they generate ROS that can break down or completely mineralize many persistent pollutants. Among the photocatalysts reviewed, TiO_2 remains the most widely used because it is stable, non-toxic, and inexpensive. Other materials, such as ZnO , $\text{g-C}_3\text{N}_4$, metal-doped photocatalysts, and heterojunction nanocomposites, have

improved visible-light absorption, charge separation, and pollutant degradation. These advances have expanded the application of photocatalysis to pharmaceuticals, antibiotics, PFAS, dyes, and endocrine-disrupting chemicals.

Despite this progress, several challenges still limit practical application. Limited visible-light activity, electron-hole recombination, catalyst recovery, nanoparticle aggregation, photocorrosion, incomplete mineralization, and the lack of large-scale studies remain important issues. In addition, the cost, long-term stability, and environmental impacts of photocatalytic systems need further evaluation.

Future research should focus on developing practical and sustainable treatment technologies rather than on increasingly complex materials. Promising directions include solar-driven photocatalysis, photocatalytic membrane systems, magnetic and multifunctional photocatalysts, hybrid adsorption-photocatalysis processes, and AI-assisted catalyst design. More pilot-scale studies using real wastewater, together with life-cycle assessment and techno-economic analysis, are also needed to evaluate the feasibility of large-scale applications. Overall, photocatalytic nanomaterials have great potential to improve water treatment and help remove emerging contaminants. Continued advances in materials, reactor design, and system optimization will support the transition of photocatalytic technologies from laboratory research to practical and sustainable water treatment.

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Conflict of interest

The author declares no competing interests.

Author contributions

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Not applicable.

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Further disclosure

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