Review Article

Photocatalytic Nanocomposites for Amoxicillin Degradation: Mechanistic Insights, Kinetics, and Environmental Implications

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ABSTRACT

This review comprehensively examines current progress in developing emerging photocatalytic nanocomposites for the degradation of amoxicillin (AMX) in wastewater treatment systems. A range of advanced nanomaterials, including mesoporous carbon nitride (MCN), TiO_2 nanoparticles, sulfur-doped $C_3N_5/DyFeO_3$, and $BiVO_4$, have demonstrated enhanced photocatalytic activity underneath visible light, primarily through the generation for reactive species such as hydroxyl as well as sulfate radicals. Special attention is given to innovative modification strategies, like heterojunction formation, elemental doping, and green synthesis routes that significantly improve photocatalytic efficiency and pollutant selectivity. Notably, MXene-based nanocomposites have achieved AMX removal efficiencies approaching 99%. The review delves into the superior photocatalytic mechanisms underlying these materials, including S-scheme heterojunctions and hybrid configurations like $Cs_3PMo_{12}O_{40}/MnIn_2S_4$, contributing to enhanced charge separation and interfacial charge transfer. Emerging systems such as α-Fe_2O_3/WO_3/activated carbon and Co_3O_4/CdO/clinoptilolite are also highlighted for their promising degradation performance under optimized kinetic conditions. Furthermore, the integration of advanced oxidation processes (AOPs) containing UV/chloramine and ozonation is discussed for their synergistic potential in reducing AMX toxicity and improving degradation rates. Complementary biological approaches, including Trametes versicolor fungi, are explored as eco-friendly alternatives for pharmaceutical wastewater remediation. This review provides critical insights into the mechanisms, kinetic optimization strategies, and ecological considerations associated with nanocomposite-based photocatalysis. Additionally, it outlines current challenges and forthcoming research directions to advance sustainable and efficient technologies for antibiotic-contaminated wastewater treatment.

Keywords

Photocatalytic nanocomposites, Wastewater treatment, Heterojunction formation, Elemental doping, Advanced oxidation processes, Visible light photocatalysis, Amoxicillin degradation, Charge separation mechanisms, Ecotoxicity, Green synthesis route, Biological remediation.

A graphical abstract of this paper is illustrated in Figure 1.

INTRODUCTION

The rapid accumulation of pharmaceutical contaminants within aquatic environments has raised serious ecological and public health concerns. Among these pollutants, AMX or amoxicillin, the most often prescribed β-lactam antibiotic, is frequently detected in wastewater due to its extensive use in medical and veterinary applications. Conventional wastewater treatment processes, including biological, chemical, and physical methods, often fail to completely remove AMX, resulting in its persistence in

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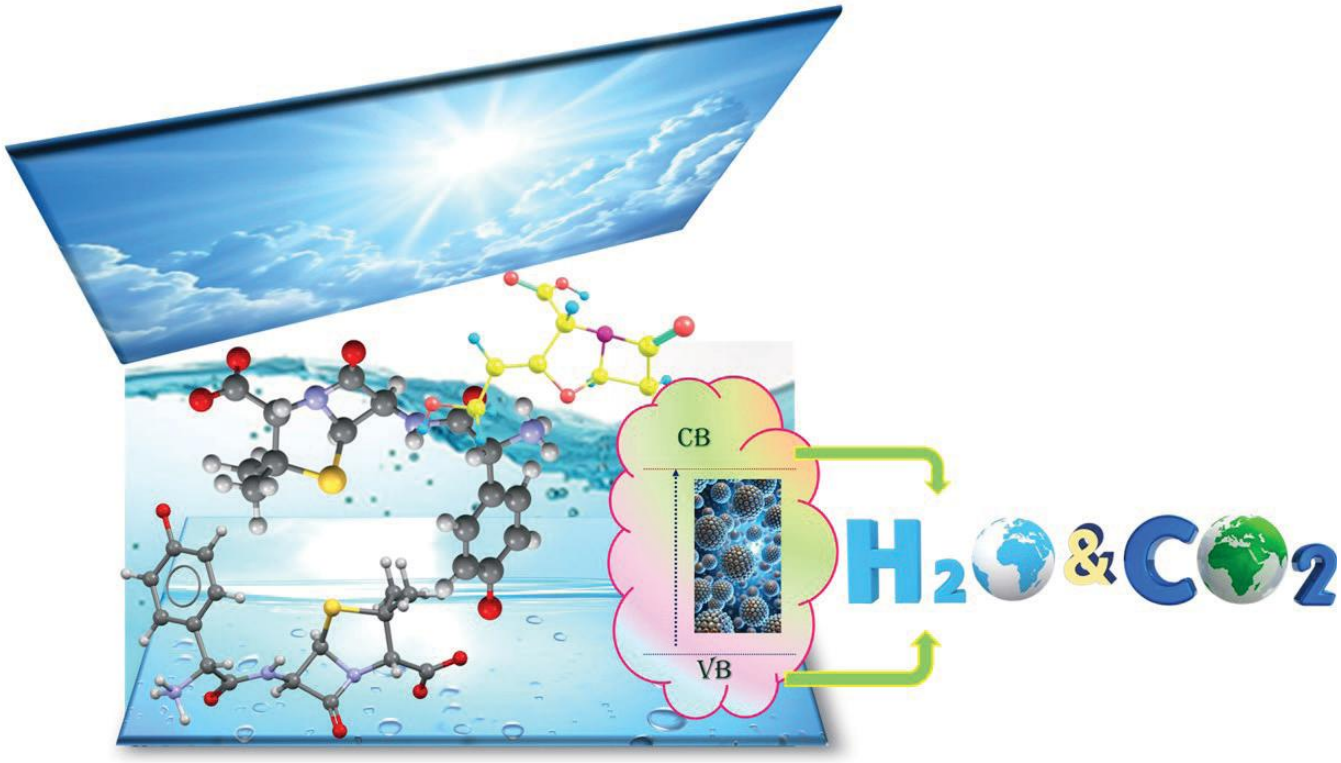

Figure 1: Graphical Abstract.
Image Credit: Pandurangan Vijayalakshmi

water bodies [1]. This incomplete degradation contributes to environmental toxicity and accelerates the emergence of antimicrobial resistance (AMR), posing a significant threat to human and ecosystem health [2]. As a result, developing efficient and sustainable strategies for AMX degradation is crucial to mitigating its long-term environmental impact [3].

Photocatalytic degradation using nanocomposite-based materials has emerged as a highly effective approach to AMX removal from wastewater [4]. Among various photocatalysts, mesoporous carbon nitride (MCN) has demonstrated superior performance under visible light irradiation, effectively enhancing degradation through hydroxyl (•OH) and sulfate radical (SO_4•$^-$) generation [5]. Several advanced materials, including TiO_2 nanoparticles, sulfur-doped C_3N_5/$DyFeO_3$, and $BiVO_4$, have also exhibited promising antibiotic degradation capabilities while minimizing toxic byproducts [6]. Additionally, MXene-based composites have gained attention for their remarkable photocatalytic efficiency, with some studies reporting up to 99% AMX removal under optimized conditions [7].

Researchers have explored strategies such as heterostructure formation, elemental doping, and biosynthesized nanoparticles to enhance photocatalytic efficacy further. The integration of S-scheme heterojunctions and hybrid systems, including $Cs_3PMo_{12}O_{40}$/$MnIn_2S_4$ [8] and plasmonic $CaIn_2S_4$/Sb_2O_3/Bi heterojunctions [9], has significantly improved charge separation and interfacial interactions, leading to enhanced degradation performance. Other promising nanocomposites, such as ZnO/g-C_3N_4 [10], Ag/Ag_2O/TiO_2 [11], CuO/Bi_2WO_6 [12], and Fe_3O_4-based photocatalysts [13], have demonstrated high photocatalytic activity due to their excellent charge transport properties and extended light absorption range [14]. Recent studies also highlighted the effectiveness of metal-organic frameworks (MOFs) and carbon-based materials, such as graphene oxide (GO), in improving the stability and reusability of photocatalysts for AMX degradation [15].

Beyond photocatalysis, advanced oxidation processes (AOPs), including UV/H_2O_2 [3], UV/persulfate (PS) [16], and ozonation [17], have been investigated for their ability to degrade pharmaceutical contaminants while

minimizing secondary pollution [18]. Moreover, biological remediation approaches, such as using Trametes versicolor fungi for cytostatic drug detoxification, offer complementary solutions for environmentally sustainable wastewater treatment [19, 20].

The precise control of energy transfer enabled enhanced electron-hole separation, achieving 93 % tetracycline degradation in 12 hours and providing insights into designing advanced photocatalysts for environmental remediation [21]. A Bi_2MoO_6/g-C_3N_4 photocatalyst with oxygen vacancies has been synthesized to enhance ciprofloxacin degradation. After four cycles, the optimized heterojunction achieved 94% removal in 90 minutes, maintaining 85% efficiency. The process proved primarily driven through holes (h^+), with LC-MS identifying possible degradation pathways [22]. A cost-effective Fe (III)-SA gel ball aerogel (FA) was developed for efficient antibiotic removal. FA attained a high NOR adsorption capacity of 338.40 mg/g and removed 97 % of NOR within 150 minutes under photocatalysis. It maintained stable performance over 10 cycles with effective regeneration. DFT analysis confirmed the degradation pathway, ensuring reduced toxicity and environmental safety [23]. It utilizes $BiVO_4$ (BVO) as a photocatalyst for water's amoxicillin (AMX) degradation. BVO150, with a bandgap of 2.36 eV, has shown the highest efficiency, achieving ≥93 % degradation in 120 minutes. The method followed a pseudo-first-order kinetic model and maintained stability over five cycles. A possible degradation of the photocatalytic mechanism and pathway has been proposed [24]. Mesoporous carbon nitride (MCN) and various advanced photocatalysts were synthesized for efficient antibiotic degradation in wastewater. These materials demonstrated enhanced charge transfer, improved light absorption, and reduced byproduct toxicity, ensuring sustainable water treatment solutions.

This review analyzes recent advancements within nanocomposite-based photocatalytic systems for AMX degradation, discussing key photocatalytic mechanisms, influencing factors, and future research directions. By exploring novel nanocomposite materials and their integration with other treatment technologies, the present research aims to benefit the development of more sustainable and efficient wastewater treatment solutions (Figure 2).

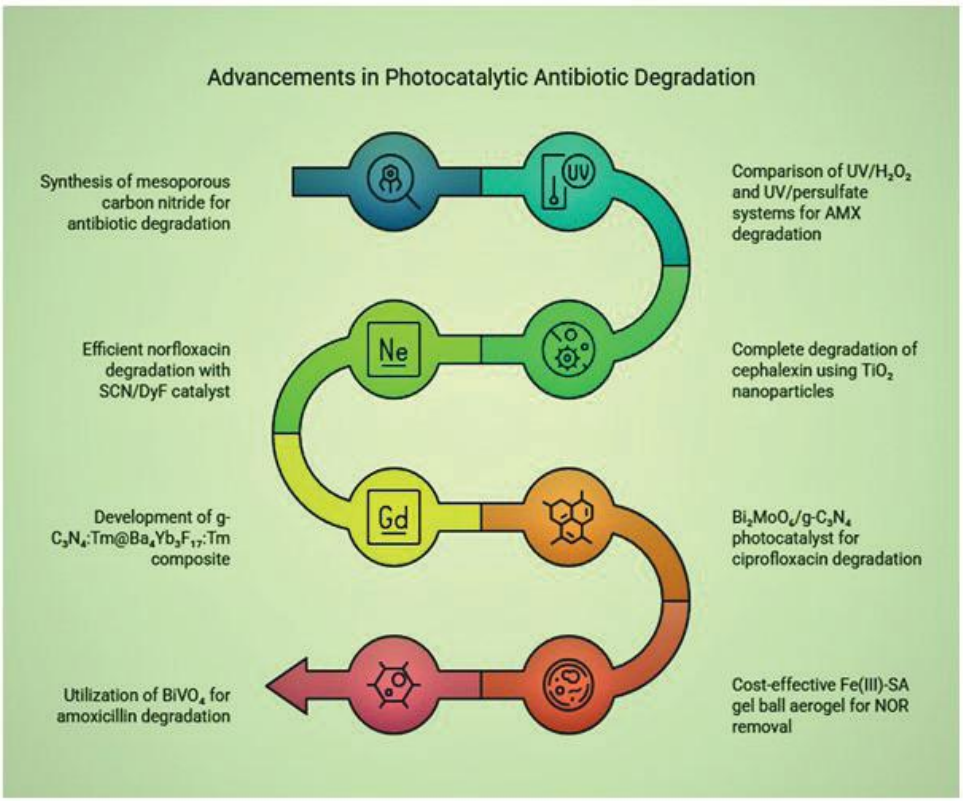

Figure 2: Advancements in photocatalytic antibiotic degradation.
Image Credit: Pandurangan Vijayalakshmi

Photocatalytic Degradation of Amoxicillin: Overview

The widespread use of antibiotics such as amoxicillin has raised growing concerns about their persistence in aquatic environments and the associated risks of antibiotic resistance. Amoxicillin, a β-lactam antibiotic commonly used in clinical and veterinary practices, often remains unmetabolized and is discharged into wastewater systems. Conventional wastewater treatment methods are largely ineffective at entirely removing such pharmaceutical residues, leading to their accumulation in surface waters and posing threats to ecosystems and human health. As a result, advanced treatment techniques, particularly photocatalysis, have emerged as promising alternatives due to their environmental compatibility and high degradation efficiency [25]. Photocatalytic degradation utilizes light-activated semiconductor materials to generate reactive oxygen species that break down organic contaminants into harmless byproducts. This section provides a comprehensive overview of the current advancements in the photocatalytic degradation of amoxicillin, highlighting key materials, degradation mechanisms, performance factors, and future perspectives for sustainable water treatment technologies. The increasing use of antibiotics raises concerns about their presence in water and the development of antibiotic-resistant genes [26]. MXene-based composites enhance photocatalytic efficiency in wastewater treatment, achieving up to 99 % degradation for the potential for environmental remediation [27]. Triclocarban (TCC) persists in water, posing ecological risks. TiO_2-zeolite nanotubes (TNZPC) achieved 95.2% degradation in greywater. Biosynthesized nanoparticles (BNPs) offer an eco-friendly alternative, reaching over 80 % degradation in 10 minutes. These sustainable methods enhance wastewater treatment efficiency [28,29]. The rise of multidrug resistance and pharmaceutical contamination threatens global health.

Biochar-based composites offer an efficient solution, with modifications enhancing photocatalytic performance. This review highlights recent advancements, degradation mechanisms, and challenges in wastewater treatment [30]. Graphitic carbon nitride (g-C_3N_4) and graphene-based materials are promising photocatalysts for antibiotic removal but face efficiency challenges. Modifications like heterostructure formation and metal doping enhance their performance and explore key advancements, degradation mechanisms, and future perspectives [31, 32]. Cr-doped TiO_2, synthesized from tannery wastewater, effectively degraded amoxicillin under visible light. TiO_2-0.33Cr showed the highest efficiency, achieving nearly 100 % degradation in three cycles. The process followed a pseudo-first-order kinetic model within an optimal rate constant for 0.004 min^{-1} [33]. MXene-based composites are cost-effective and highly efficient for antibiotic degradation. Their superior catalytic activity stems from increased surface area and enhanced optical properties. Amoxicillin photodegradation accelerates at higher pH but slows in high salinity conditions. Hydroxyl radicals (•OH) play a key role in the photocatalytic degradation process [34,35]. Drugs play a vital role in disease management but also pose health and environmental risks. Effective degradation methods, including photocatalysis, are essential for mitigating their impact. Carbon-based materials like graphene and its derivatives show promise in drug degradation. This review highlights their potential in photocatalytic applications [35]. Degradation of photocatalytic was a sustainable method of removing pharmaceutical contaminants from water. MOF-based nanocomposites, with high surface area and functionality, enhance pollutant breakdown (Figure 3).

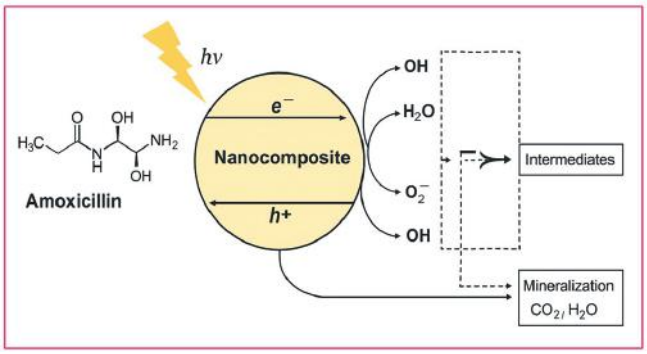

Figure 3: Mechanism of Photocatalytic Degradation of Amoxicillin Using Nanocomposites.
Image Credit: Pandurangan Vijayalakshmi.

This review explores their synthesis, efficiency, and modifications for improved stability [26]. MXene is a promising photocatalyst of pharmaceutical degradation in aqueous under simulated sunlight. Its unique structure, high conductivity, and active functional groups enhance performance and stability. Heterostructured MXene-based catalysts efficiently remove pharmaceutical waste and antibiotics. Photocatalytic degradation effectively eliminates organic pollutants like antibiotics, dyes,

and hydrocarbons. Modified photocatalysts, such as doped metal oxides and composites, enhance efficiency by improving light absorption and charge separation. Optimized conditions, including temperature, pH, and catalyst concentration, significantly boost degradation rates for sustainable environmental remediation [36, 37]. The increasing presence of antibiotics in water raises concerns about resistance and contamination (Figure 4).

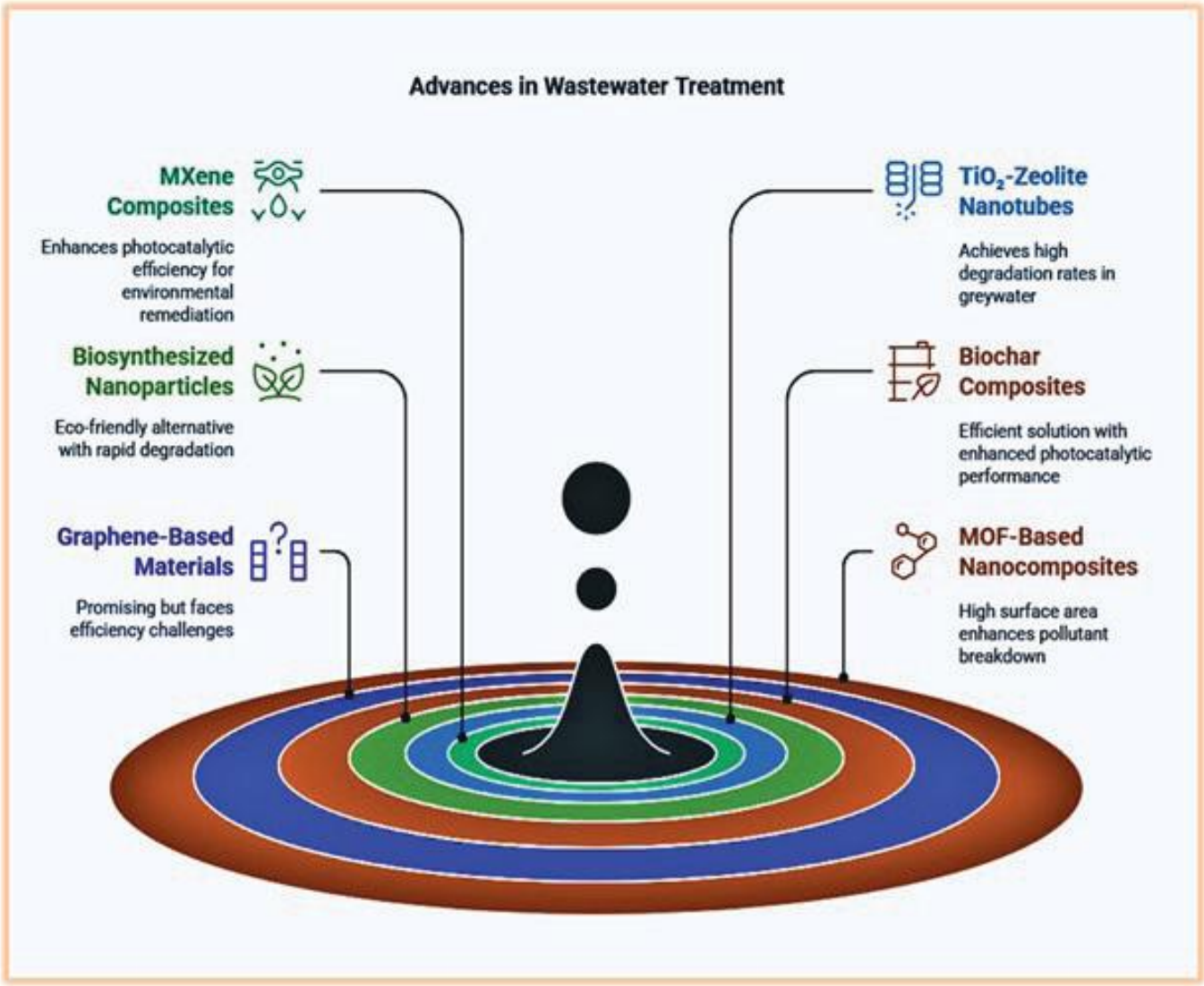

Figure 4: Advances in wastewater treatment.
Image Credit: Pandurangan Vijayalakshmi.

MXene-based and biochar composites enhance photocatalytic degradation, achieving up to 99 % efficiency. Modified photocatalysts like MOFs and doped TiO_2 offer sustainable solutions for wastewater treatment.

Photocatalysis: Principles and Mechanism

Photocatalysis is a promising green technology for addressing energy and environmental challenges. By harnessing solar energy to activate semiconductor materials, photocatalysis enables a range of chemical transformations, including the degradation of organic pollutants, hydrogen production, and carbon dioxide reduction [38]. This light-induced catalytic process offers several advantages, such as low energy consumption, environmental friendliness, and potential for large-scale applications. Traditional photocatalysts like titanium dioxide (TiO_2) and zinc oxide (ZnO) have been widely studied for their photocatalytic efficiency,

stability, and availability [39]. However, these materials face challenges such as wide band gaps and limited visible light absorption. To overcome these limitations, significant research efforts have been directed toward the development of modified semiconductors, including graphitic carbon nitride (g-C_3N_4), metal-organic frameworks (MOFs), and a variety of heterojunction-based nanocomposites [40] (Table 1).

Table 1: Physicochemical Properties of Amoxicillin Relevant to Photocatalysis

Property	Value / Description	Relevance to Photocatalysis	Reference
Chemical Name	Amoxicillin trihydrate	Identifies the compound under study	41
Molecular Formula	$C_{16}H_{19}N_3O_5S$	Helps determine degradation pathways and stoichiometry	42
Molecular Weight	365.40 g/mol	It affects diffusion and adsorption behavior on catalyst surfaces	43
Structure	β-lactam ring with amino and hydroxyl groups	Functional groups affect interaction with active sites and ROS	44
pKa values	~2.4 (carboxylic), ~7.4 (amino), ~9.6 (phenolic)	Determines ionization state in aqueous media and optimal pH for degradation	42
Solubility in Water	Highly soluble (4 mg/mL at 25°C)	Facilitates aqueous photocatalytic treatment	45
Log Kow (octanol-water)	−1.07	Indicates hydrophilicity and low bioaccumulation potential	46
UV Absorption λ_{max}	~230 nm and ~270 nm	Relevant for UV/Vis-based degradation and analytical monitoring	42
Photolysis Stability	Moderately stable under light	Justifies the need for photocatalysts to enhance degradation	47
Biodegradability	Poorly biodegradable	Emphasizes the importance of advanced oxidation processes like photocatalysis	48
Antibacterial Activity	Broad-spectrum (Gram-positive and some Gram-negative)	Highlighting ecological risk if unmetabolized in the environment	49

Table Credit: Pandurangan Vijayalakshmi.

This section reviews the fundamental principles of photocatalysis, including light absorption, charge carrier generation, separation, surface redox reactions, and recombination processes. It also highlights the mechanisms of advanced photocatalytic systems such as Z-scheme, S-scheme, and p–n junction heterostructures. Emphasis is placed on design strategies, materials engineering, and recent innovations to enhance photocatalytic efficiency for environmental and energy-related applications. Photocatalysis offers a sustainable approach to pollution control and solar energy storage. Z-scheme photocatalysts, including MnO_2-based composites, enhance electron transport and degradation efficiency [50]. Semiconductor photocatalysis is widely used for pollutant degradation and hydrogen production but suffers from rapid charge carrier recombination. Various heterostructures have been explored to enhance charge separation, including type II, Z-scheme, p–n junctions, and Schottky junctions. Recently, S-scheme heterojunctions have shown superior charge preservation for photocatalytic reactions. This review discusses their charge transfer mechanisms, key semiconductors, identification methods, challenges, and prospects [51].

Photocatalysis utilizes photon energy to drive chemical reactions via electron, energy, or atom transfer. Photoredox catalysis, employing photocatalysts as oxidizing and reducing agents, has revolutionized fields like organic synthesis, biomedicine, and environmental management. Recent studies highlight the need to improve efficiency, recyclability, and ecological impact. This review explores the fundamentals, applications, and prospects of photocatalysis [52]. Photocatalysis in environmental and energy applications is hindered by rapid charge recombination, with built-in electric fields (BIEFs) offering a solution. This review explores

polarization and interface BIEFs, their synergy with external fields, and novel self-healing mechanisms. Analytical methods and driving mechanisms in photocatalysis are discussed, and finally, the challenges and prospects of BIEFs [53] are discussed. Nano-energetic semiconductor-based photocatalysis efficiently utilizes solar energy for fuel generation and contaminant removal but faces challenges like rapid charge recombination and low light utilization. Well-designed heterojunction photocatalysts enhance charge separation, improving efficiency. This review explores photocatalysis principles, classifications, and applications, including optical and electronic properties. Recent advancements in heterojunction photocatalysts for environmental and energy applications are discussed.

Finally, future research directions in nano-energetic photocatalysts [54]. Photocatalysis is a sustainable approach for environmental remediation, with applications in dye degradation, CO_2 and NO_x reduction, and hydrogen generation. Enhancing efficiency relies on minimizing electron-hole recombination, often achieved through heterojunction formation. Various semiconductor materials and heterojunction types are explored for optimized performance. This review discusses fundamental principles, charge transfer mechanisms, and strategies for designing efficient heterojunctions [55]. S-scheme heterojunction photocatalysts enable efficient solar-to-chemical conversion for sustainable energy production. Research has traditionally focused on band structure alignment, but this review highlights factors like light absorption, interfacial recombination, selective contact, and ferroelectric polarization. Different charge transfer pathways are analyzed using band structure theory. Design strategies for optimizing S-scheme heterojunctions are proposed [56]. Photocatalytic technology has a cost-effective and environment-friendly approach to removing organic pollutants. TiO_2-conjugated/coordination polymer heterojunctions have emerged as promising photocatalysts for environmental remediation. This review explores their classifications, synthesis, photocatalytic mechanisms, and performance—prospects and challenges in advancing TiO_2-based heterojunction photocatalysts [57]. It examines recent advancements in photocatalytic methods for plastic pollution remediation. It covers fundamental principles, photocatalysts, and factors influencing degradation efficiency. Challenges, environmental impacts, and the potential for converting plastic waste into valuable products are discussed (Figure 5). Industrial applications, scalability, and future research directions [58]. Photocatalysis enables sustainable pollution control and energy storage. This review explores advancements in photocatalysts, charge transfer mechanisms, and prospects.

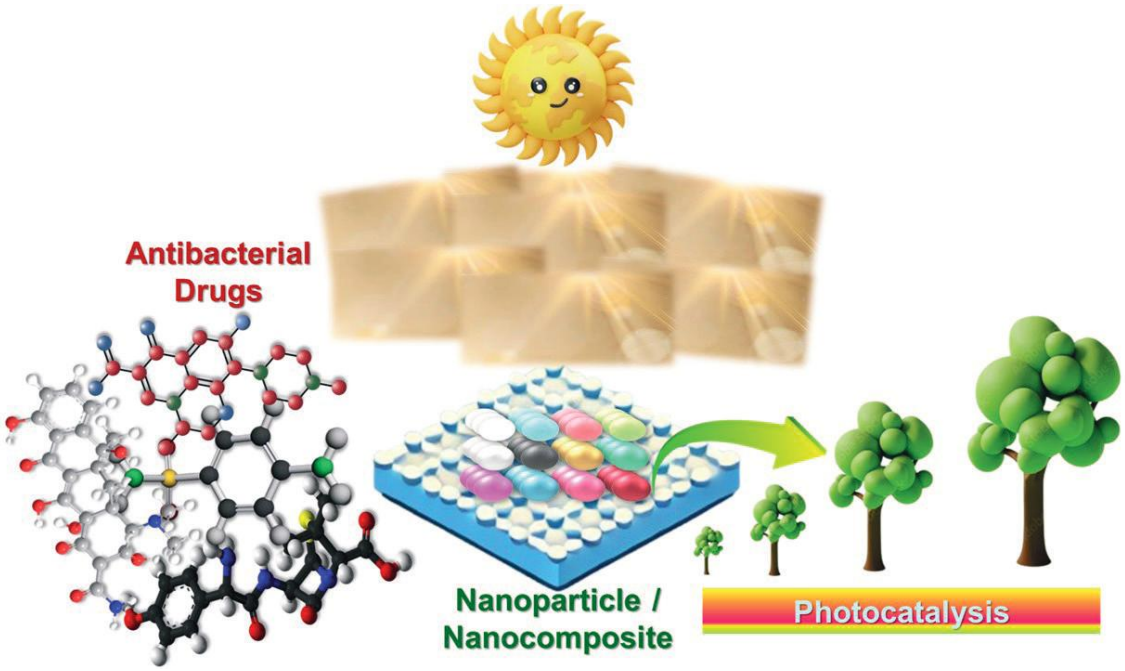

Figure 5: Schematic Illustration of Photocatalysis Principles.
Image Credit: Pandurangan Vijayalakshmi.

Fundamentals of Photocatalysis

These covalent triazine frameworks (CTFs) are highly stable, nitrogen-rich porous materials with applications in gas purification, energy storage, and photocatalysis. Different synthesis techniques have been developed to enhance their structural and functional properties. This review explores recent advancements in CTF synthesis, functionalization, and photocatalytic performance, along with prospects for optimizing CTFs in energy and environmental applications [59]. Photocatalysis and photoelectrocatalysis are promising methods for solar energy conversion but still face challenges related to efficiency. Recently, polarons have emerged as key factors in enhancing catalytic performance. This review highlights polaron models, experimental observations, and their role in improving the performance of photocatalysts and photoelectrodes, offering insights into mechanism optimization and efficiency enhancement [60]. Piezopolarization-driven photocatalysis improves solar-to-chemical conversion by utilizing a piezoelectric field for effective charge separation. It contributes to fundamental reactions, such as H_2O_2 production and detection techniques. Recent advancements and theoretical insights focus on improving efficiency for green energy applications [61].

Photocatalytic water splitting and CO_2 reduction are vital for addressing energy and environmental challenges. While direct Z-scheme heterostructures improve charge separation, they also face crystal defects. Van der Waals heterostructures offer a solution by preserving material properties. This summarizes recent advances and design strategies for efficient photocatalysts [62]. The global transition to renewable energy is crucial for reducing CO_2 emissions. Electrocatalytic and photocatalytic CO_2 reduction to methane presents a sustainable approach. This explores reaction mechanisms, catalyst design, and the associated challenges in implementing this technology [63]. Hydrogen peroxide (H_2O_2) plays a significant role in water treatment and chemical synthesis. Its photocatalytic production using Z-scheme systems has gained attention due to improved electron transfer and reaction efficiency, advancements, challenges, and prospects [64]. Photocatalysis has a promising green technology for solar energy conversion and environmental remediation. X-ray absorption spectroscopy (XAS) provides atomic-level insights into photocatalyst structures and reaction mechanisms. Time-resolved XAS enables real-time monitoring of photocatalytic processes in exploring XAS applications in photocatalysis and future research directions [65]. CTFs are stable, nitrogen-rich materials with applications in energy and environmental fields of recent advancements in their synthesis, functionalization, and photocatalytic performance.

Common Photocatalysts Used (e.g., TiO_2, ZnO, g-C_3N_4, Nanocomposites)

Solar-driven photocatalysis has emerged as a sustainable and efficient method for environmental remediation, including hydrogen production, CO_2 reduction, and, notably, the degradation of pharmaceutical pollutants like AMX. Among the various semiconductors, graphitic carbon nitride (g-C_3N_4), titanium dioxide (TiO_2), and Zinc oxide (ZnO) have been widely explored due to their suitable band gaps and strong redox capabilities. For instance, graphitic carbon nitride/strontium titanate/zinc oxide (g-C_3N_4/$SrTiO_3$/ZnO) nanocomposites achieved 96% degradation of Cefixime, showcasing their potential for antibiotic pollutant removal [66]. Similarly, graphitic carbon nitride (g-C_3N_4) and ZnO semiconductors (ZnO/g-C_3N_4) hybrids demonstrated superior self-cleaning and antibacterial properties in treated fabrics, indicating potent ROS (reactive oxygen species) generation and surface activity [67]. These composites benefit from enhanced visible-light absorption, increased surface area, and better charge separation, which are essential for photocatalytic efficiency.

A green-synthesized (ZnO/g-C_3N_4) coating tested in a flow reactor achieved 100 % degradation of ciprofloxacin under concentrated sunlight in 210 minutes, proving the composite's effectiveness in solar-driven systems [68]. TiO_2/g-C_3N_4 heterojunctions have been developed to optimize electron-hole separation, narrow the band gap, and improve AMX degradation under visible light conditions [69].

The photocatalysts summarized in Table 2 represent a broad spectrum of engineered nanomaterials with tunable band gaps, enhanced interfacial properties, and hybrid heterojunction structures that significantly improve AMX degradation efficiency. These include widely used materials such as TiO_2, ZnO, and g-C_3N_4, as well as more advanced configurations like Ag/ZnO, Mn-Cu_2O, and black TiO_2, each offering unique advantages in terms of reusability, band alignment, and ROS generation mechanisms.

Table 2: Overview of Advanced Photocatalysts Employed in the Degradation of Amoxicillin: Band Gap, Mechanism, and Efficiency

Photocatalyst	Band Gap (eV)	Key Features	Advantages of Amoxicillin Degradation	Reference
TiO_2 (anatase)	~3.2	UV-active, stable	Strong oxidizing power	70
ZnO	~3.2	High electron mobility	Comparable to TiO_2, antibacterial	71
g-C_3N_4	~2.7	Visible-light responsive	Metal-free, tunable	2
TiO_2/g-C_3N_4 (Heterojunction)	2.6–3.0	Type-II heterojunction	Enhanced e^-/h^+ separation	72
ZnO/CdS	2.4–3.2	Heterojunction	Visible-light responsive	73
Ag/ZnO	~3.2	Plasmonic Ag NPs	Enhanced ROS generation	74
BiVO4	~2.4	Visible-light active	Environmentally friendly	75
Mn-Cu_2O	~2.0	Narrow bandgap	Red-light active	76
Cu-WO_3	~2.8	Acid stable	Visible-light driven	77
TiO_2/Fe_2O_3	~2.1	Earth-abundant	Magnetic recovery	78
MoS_2	~1.8	2D material	Charge separation booster	79
SnO_2	~3.6	UV active	High e^- conductivity	80
ZnO/Bi_2O_3	~2.8	Layered oxide	Visible-light responsive	81
CuO/SiO_2	~1.5	Narrow bandgap	Visible light responsive	82
NiO	~3.4	p-type semiconductor	Active sites for oxidation	83
ZnO-CeO_2	~3.2	Oxygen vacancies	Reactive oxygen species generator	84
MnO_2	~1.3	Strong oxidizer	Dual redox states	85
ZnO-rGO	~3.2	Hybrid material	Electron mobility enhanced	86
BiOI	~1.8	Narrow bandgap	Visible light enhancement	87
Fe-Bi_2WO_6	~2.7	Layered Aurivilius oxide	Stable under visible light	88
difluoride/graphene/ $ZnFe_2O_4$	~1.9	Magnetic spinel	Visible, active, reusable	89
TiO_2/single-walled CNTs	~3.2	Carbon support	Increased surface area	90
Black TiO_2	~2.0–2.6	Reduced form	Enhanced visible-light absorption	91

Notes: "UV-active" refers to a substance that interacts with and absorbs ultraviolet (UV) light, while "UV-stable" means a material can withstand the damaging effects of UV light without significant degradation; Plasmonic Ag NPs denotes silver nanoparticles exhibiting plasmonic effects. **Table Credit:** Pandurangan Vijayalakshmi.

Mechanisms of Amoxicillin Degradation via Photocatalysis

Antibiotics such as AMX in aquatic environments pose significant ecological and health risks due to their persistence, bioaccumulation, and potential to induce antimicrobial resistance. Conventional wastewater treatment processes often fail to completely remove these micropollutants, necessitating the development of advanced remediation strategies. Among them, semiconductor-based photocatalysis has emerged as a promising technique for efficiently degrading antibiotics under light irradiation. Recent advances focus on engineering photocatalysts with enhanced light absorption, charge carrier separation, and redox capabilities. Various strategies have improved photocatalytic efficiency, including constructing S-scheme heterojunctions, integrating plasmonic materials, and developing multifunctional nanocomposites. The following studies highlight recent innovations in photocatalyst design and their mechanisms in degrading antibiotics like tetracycline,

ciprofloxacin, and others, offering insights into their environmental applicability and effectiveness.

An S-scheme $Cs_3PMo_{12}O_{40}/MnIn_2S_4$ (CPM/MIS) core-shell heterojunction has been developed for efficient antibiotic and Cr (VI) removal. The optimal 9% CPM/MIS achieved 97.81 % tetracycline, 61.78 % ciprofloxacin, and 67.07 % Cr (VI) degradation under visible light. Its superior performance was attributed to enhanced charge separation, strong interfacial interactions, and improved redox activity. ESR and XPS analyses confirmed the S-scheme mechanism, offering a promising strategy for contaminant removal [92]. The MoS_2-based photocatalyst nanocomposites and aerogels for antibiotic degradation highlight their structure, optical properties, and photocatalytic mechanisms. The review examines synthesis methods, the transfer of photoelectron pathways, and the involvement of reactive oxygen species (ROS). Challenges and future perspectives are discussed to advance MoS_2-based photocatalysts for environmental applications [93]. A plasmonic $CaIn_2S_4/Sb_2O_3/Bi$ heterojunction has shown efficient antibiotic photodegradation under LED light irradiation. The $CaIn_2S_4/Sb_2O_3/Bi$-10 % hybrid achieved up to 97.4 % degradation of antibiotics, with effective photocatalytic performance due to the synergistic effects of the S-scheme system and plasmonic Bi^0. The catalyst also demonstrated excellent TOC reduction and charge separation efficiency [9]. The ZnO/Bi_2MoO_6/ZIF-67 photocatalyst was investigated for tetracycline

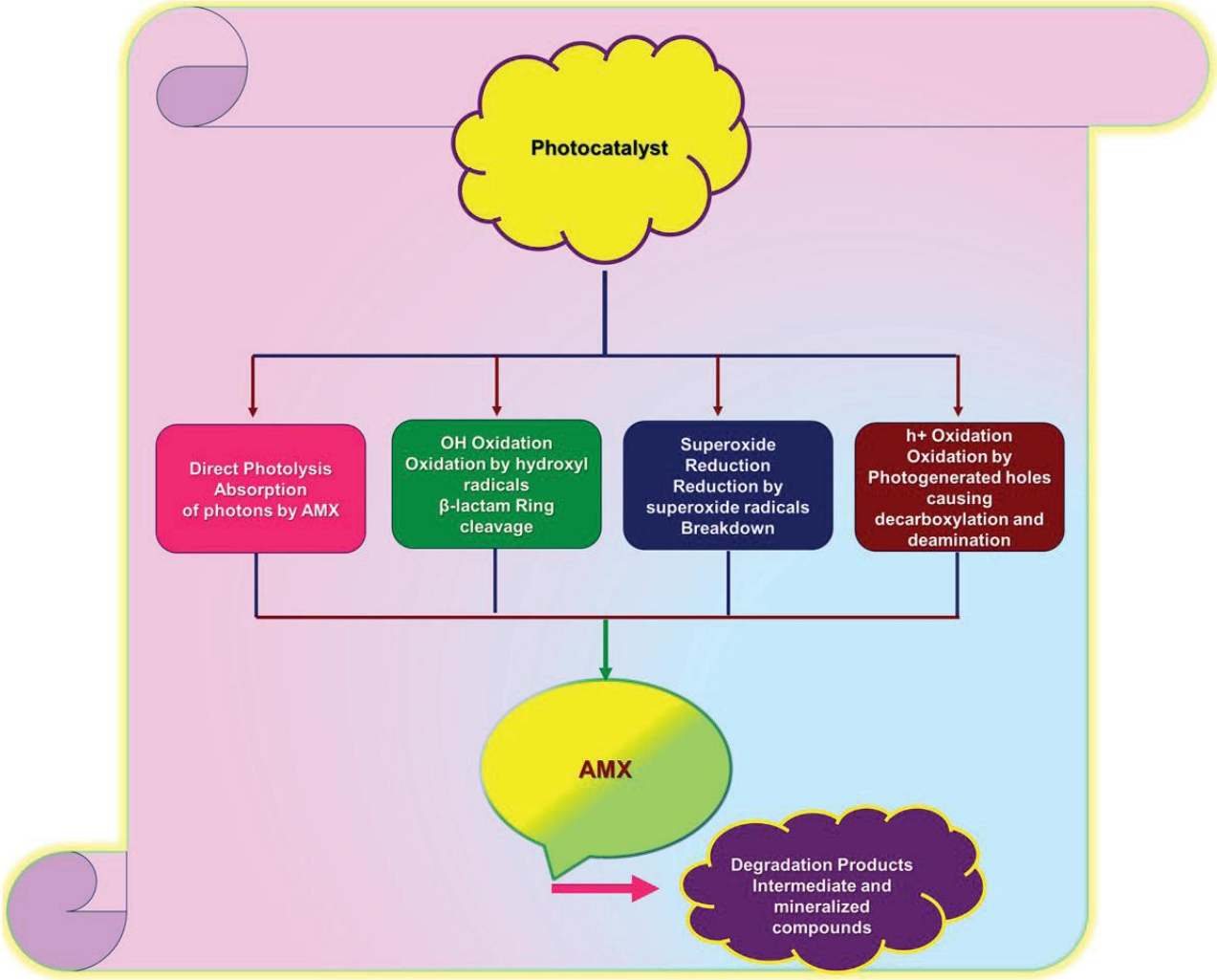

Figure 6: Schematic Representation of Photocatalytic Degradation Routes of Amoxicillin.
Image Credit: Pandurangan Vijayalakshmi.

degradation underneath visible light. The optimal molar ratio (ZnO: Bi_2MoO_6: ZIF-67 = 1:0.6:0.157) achieved 90.3% tetracycline removal under ideal conditions. The degradation followed first-order kinetics, with OH• and $•O_2^-$ species significantly enhancing the process (Figure 6).

The composite outperformed individual components, offering a promising solution for antibiotic removal [94]. A self-standing dual-electric field synergistic Janus nanofiber photocatalyst ([TP]/[CTP]JNs) was developed using conjugate electrospinning—the dual electric fields, from the S-scheme heterostructure and piezoelectric PVDF, enhanced charge separation and transfer. The photocatalytic efficiency for tetracycline degradation under combined ultrasonic and sunlight illumination reached 93.35%. This approach outperformed light-only and ultrasonic-only methods, demonstrating the benefits of the synergistic piezoelectric-photocatalytic effect [95]. It introduces novel photocatalysts, including the S-scheme CPM/MIS core-shell heterojunction and plasmonic $CaIn_2S_4/Sb_2O_3$/Bi hybrid, enhance antibiotic and contaminant degradation through synergistic effects and improved charge separation. The development of dual-field Janus nanofibers and MoS_2-based nanocomposites offers efficient, sustainable solutions for environmental pollutant removal.

Influence of Operational Parameters (Light Source, pH, Pollutant Concentration and Catalyst Dosage)

The efficiency of photocatalytic degradation processes is strongly influenced by operational parameters such as light source, pH, pollutant concentration, and catalyst dosage, making their optimization essential for enhancing contaminant removal and ensuring reliable performance in wastewater treatment applications. A novel α-Fe_2O_3/WO_3/AC photocatalyst has been synthesized from Rosa Canina seeds to improve degradation efficacy by reducing electron-hole recombination and preventing nanoparticle aggregation. The optimal catalyst (50 wt.%: FeW/AC3–500) achieved 98.01% doxycycline degradation within a rate constant of 0.030 min^{-1}. Trapping experiments identified $•O_2^-$ and •OH as key reactive species. Transient photocurrent and EIS measurements confirmed enhanced charge separation, improving photocatalytic activity. This approach offers a promising solution for wastewater treatment and environmental remediation [96]. Photocatalysis is environmentally friendly and includes cost-effective processes for wastewater treatment, with semiconductor nanoparticles playing a key role. This study optimized operational parameters for photocatalytic degradation of synthetic wastewater using $CaTiO_3$ nanoparticles. The best performance was achieved in 33 W UV light sources, pH 6.0, and catalyst dose of 3.33 g L^{-1}, resulting in 77-100% COD removal. $CaTiO_3$ exhibited a band gap of 3.57 eV and a particle size of less than 47.62 nm [97]. Another investigation explored the photocatalytic degradation for acetaminophen (ATP) and sulfadiazine (SFZ) utilizing green-synthesized ZnO nanoparticles derived from neem leaf extract. These nanoparticles were immobilized on carbon from spent tea waste (N-ZnO@TAC) to enhance recovery and reuse. Under optimal conditions, N-ZnO@TAC achieved 100% removal of both contaminants. The degradation pathways were analyzed using LC-MS. N-ZnO exhibited superior antibacterial properties compared to TAC and N-ZnO@TAC, demonstrating its potential for wastewater treatment [98].

A GO/MgO nanohybrid was developed as a photocatalyst and a periodate (PI) activator of degrading reactive blue-222 dye, sulfamethazine, and atrazine. The composite showed improved charge separation and high stability across multiple cycles. Under optimal conditions, it achieved 97.3 % degradation of RB-222 in 120 minutes and effectively degraded other pollutants. The system's performance was reduced in canal and seawater, demonstrating its potential for industrial effluent treatment [99]. A stable and reusable CeO_2/WO_3/AC photocatalyst was synthesized and optimized for doxycycline (DOX) degradation using Central Composite Design (CCD). Characterization techniques revealed the catalyst's properties and determined operational parameters for efficient degradation. The optimal photocatalyst achieved 97.23 % DOX degradation and 83.11 % of COD removed. h^+ also $•O_2^-$ radicals played a key role within the photocatalytic degradation processes. The catalyst maintained high stability after five degradation cycles [100]. A Co_3O_4/CdO/clinoptilolite (CCC) heterojunction photo nanocomposite was developed as an efficient S-scheme photocatalyst for degrading levofloxacin underneath sunlight. CCC exhibited superior performance, achieving near-total degradation within a reaction rate constant of 0.0412120 min^{-1} underneath optimal conditions. The composite demonstrated excellent stability, recyclability, and antimicrobial activity. This research provides valuable insight into the design of ternary nanocomposites for effective

pollutant photodegradation and diverse applications [101]. Overall, novel photocatalysts, including α-Fe_2O_3/WO_3/AC, N-ZnO@TAC, and Co_3O_4/CdO/clinoptilolite, demonstrated efficient degradation of various pollutants such as doxycycline, acetaminophen, also levofloxacin. These composites showed enhanced photocatalytic performance, high stability, and reusability, offering promising solutions for wastewater treatment and environmental remediation.

Degradation Byproducts and Toxicity

Understanding the degradation pathways and associated toxicity of pharmaceutical contaminants is crucial for evaluating the environmental risk of their removal processes. Various studies have explored the transformation of these compounds through different advanced oxidation processes and biological treatments, highlighting the formation of intermediate byproducts, their potential toxicity, and the overall effectiveness of the methods used [102,103]. Different pathways of AMX degradation have been proposed, including the opening of the four-membered β-lactam ring, followed by oxidation of the methyl group to an aldehyde and/or hydroxylation of the benzoic ring. These processes generate various intermediates through bond cleavage between different atoms and subsequent oxidation to carboxylates such as acetate, oxalate, and propionate, along with the formation of nitrate and ammonium [104]. The use of white-rot fungi for removing anticancer drugs bleomycin and vincristine from wastewater has shown promising results. Fungi like Trametes versicolor and Hypholoma fasciculare achieved over 90 % removal of vincristine within two days, with oxygen supply enhancing degradation. Laccase activity was linked to drug elimination. The process also demonstrated detoxification, highlighting fungi as a promising solution for cytostatic removal [105]. The thermo-activation for periodate (heat/PI) for water pollution removal has been underexplored. This study evaluates the heat/PI system using tetracycline antibiotics as a model pollutant. The system showed effective remediation with increased temperature. Quenching and electron paramagnetic resonance experiments identified the reactive oxidative species, and density functional theory calculations revealed potential reactive sites in tetracycline. Toxicity estimation of byproducts showed no significant differences across temperatures, providing insights into the oxidation power, byproduct transformation, and system toxicity of the system [106].

Ambroxol (AMB) degradation within the UV/chloramine method, identifying reactive chlorine and nitrogen species as key radicals. Debromination occurred mainly within the initial stage, with a 34.5 % rate at 10 minutes. Four photodegradation pathways have been proposed, and toxicity risks were assessed using the ECOSAR model. The UV/chloramine processes effectively remove AMB while reducing the formation of brominated disinfection byproducts (Br-DBPs), showing promise for water treatment applications [107]. The degradation of 6PPD-Q using a UV/PMS process, revealing complete degradation at a PMS/6PPD-Q ratio of 60:1. SO_4•− and •OH radicals were key to its removal, with toxicity prediction showing reduced risks from the degradation products. In another study, a hybrid CuxFe1-xZnO-LDO/PMS/US system efficiently degraded ofloxacin (OFC), including reduced total organic carbon (TOC) from pharmaceutical wastewater, demonstrating excellent catalytic activity and reduced biotoxicity. The system also showed stability with minimal metal ion leaching and an estimated treatment cost of $0.059/L [108, 109]. Spinel $MnFe_2O_4$ was synthesized to activate periodate (PI) to degrade sulfamethoxazole (SMX), with 500-MFO showing superior activity and selectivity. Multiple active species, such as IO_3•, •OH, and Mn (IV), were identified, with IO_3• as the primary species. PMSO promoted Mn (IV) regeneration, enhancing SMX degradation. Toxicity predictions showed that while intermediate byproducts varied in toxicity, the final products have been environmentally benign, offering viable processes for SMX degradation within wastewater treatment [110]. Ozonation effectively degrades and mineralizes pharmaceutical compounds, with over 97% removal in pH 10 conditions and an ozone dose of 1.0 g. L^{-1}. Mineralization increased under alkaline conditions, with rates of 22.3 % for CAF, 20.8% for AMP, and 34.04 % in a composite matrix. Post-ozonation concentrations have below toxic limits predicted through QSAR-OECD. Moreover, research on the toxicity of the byproducts is needed to assess the process [111] fully. The effective use of advanced oxidation processes, including UV/chloramine, UV/PMS, and ozonation, has demonstrated efficient degradation of pharmaceutical contaminants with minimal byproduct toxicity. The methods offer sustainable solutions for treating complex pharmaceutical pollutants in wastewater [103].

Kinetics and Reaction Pathways in Advanced Photocatalytic Systems

The efficiency of emerging catalytic systems relies heavily on a deep understanding of their reaction kinetics and underlying mechanistic pathways. In photocatalytic CO_2 reduction (CO_2RR), key factors such as photo-excitation, electron-hole pair separation, and CO_2 activation play critical roles. Optimization strategies like defect engineering, doping, and co-catalyst loading are employed to improve conversion rates and product selectivity. Various catalyst types, including TiO_2, carbon nitride, and Cu-based materials, have demonstrated promising performance [112]. In parallel, advancements in thermal stability and combustion characteristics for polyimide (PI) aerogels have been observed.

In-situ scanning electron microscopy reveals pore structure evolution and fiber expansion under increased temperatures. The pyrolysis mechanism was analyzed through synchrotron photoionization mass spectrometry, revealing a three-stage thermal decomposition process offering insights into PI aerogel applications under thermal conditions [113]. In zinc-air batteries (ZABs), hydrophilic porous carbon materials exhibit inner surface ion confinement effects that enhance cathodic reaction kinetics in neutral media. The microporous structure temporarily stores OH^- ions, shifting the reaction pathway toward a more efficient electrolyte mechanism. This reduces zinc salt precipitation and overpotentials, improving energy efficiency from 46.0% to 74.5%. These advances enable scalable applications using a 10 Ah pouch and flexible cells [114].

Catalyst engineering has also shown potential in tuning strain and reactivity. For instance, cerium dioxide (CeO_2) can modulate in-plane strain in 2D metastable 1T-phase IrO_2, resulting in improved catalytic performance. A 5% CeO_2-loaded 1T-IrO_2 within 8 % compressive strain achieves a low overpotential (194 mV) and excellent stability up to 400 hours. This material follows a distinct *O–*O radical coupling mechanism of O_2 evolution, offering a robust electrochemical pathway [115].

These studies reveal degradation efficiencies ranging from 65-100% depending on the catalyst, light source, and reaction conditions. For instance, $CdS/NH_4V_4O_{10}$ achieved 94.4% degradation of AMX under sunlight in 120 minutes, while TiO_2-0.33Cr reached 100% degradation in 180 minutes under the same conditions. A detailed comparison of photocatalysts for antibiotic removal underneath different light sources is presented in Table 3. The principal findings of this narrative are depicted in Figure 7.

Table 3: Comparison of Photocatalysts for Antibiotic Removal Under Different Light Sources.

Serial No.	Catalyst	Antibiotic	Light Source	Degradation Efficiency (%)	Duration (min)	Ref.
1	metal-free polymeric carbon nitrides	AMX	xenon lamp – Visible Light	100	48 h	116
2	Commercial TiO_2	AMX	Sun Light	89.31	120	117
3	Commercial TiO_2	Ciprofloxacin	Sun Light	90.2		
4	N-TiO_2	AMX	Sun Light	95.8		
5	N-TiO_2	Ciprofloxacin	Sun Light	97.3		
6	p-n heterojunction CuI/$FePO_4$	AMX	Sun Light	90		118
7	CuI			41		
8	$FePO_4$			69		
9	UVC/$S_2O_8^{2-}$ and UVCS2O8^{2-}/Fe^{2+}	AMX	Mercury germicidal lamp	99	2 h	119

Serial No.	Catalyst	Antibiotic	Light Source	Degradation Efficiency (%)	Duration (min)	Ref.
10	2D/2D Bi_2WO_6/Ti_3C_2	AMX	Solar lamp	100	40	120
11	UV/TiO_2	AMX	UV lamp (100 W)	70	120	121
		Metronidazole				
12	V_2O_5/C_3N_4	AMX	Solar Light	91.3		122
13	N-TiO_2	AMX	Blue LED Light	65.3	90	123
14	TiO_2/single-walled carbon nanohorns	AMX	UV light	92.4%	90	90
15	$CDs/NH_4V_4O_{10}$	AMX	Sun Light	94.4	120	124
16	TiO_2-o.33Cr	AMX	Sun Light	100	180	33
17	Bi_2WO_6/nano-ZnO	AMX	Visible Light	93.10	2 h	125
18	$Zn_xCo_{1-x}Fe_2O_4$	AMX	Visible Light	89	180	126
19	$BiVO_4$	AMX	Sun Light	98.6	90	127
20	$Ag/Ag_2O/TiO_2$	AMX	Visible Light	97.91	90	11
21	$Ba(Ti_{0.950}Sc_{0.025}Nb_{0.025})O_3$	AMX	Solar Light	72	123	128
22	TiO_2/zeolite	AMX	Ultra Visible light Irradiation	99.8	240	129
23	Green Extract (*Camellia sinensis* var. *assamica)*/SnS_2	AMX	Visible Light	93.72	90	130
		Congo Red		98.43		
24	Mesoporous g-C_3N_4	AMX	Visible Light	90	60	2
		Cefotaxime		99		
25	CuO/activated carbon	AMX	Solar	98	90	131
26	Pt–Bi–TiO_2	AMX	Visible light 300 W halogen–tungsten lamp	87.67%	120	132
27	$UV/g-C_3N_4$	AMX	Visible Light 500 W halogen lamp	53	120	133
	$UV/Fe_3O_4/g-C_3N_4$			34		
	$Visible/Fe_3O_4/g-C_3N_4$			81		
28	TiO_2/Fe_2O_3	AMX	Solar Light	96.5	50	78
29	*p*-CuO/*n*-ZnO	AMX	Solar Light	90	240	134
30	$Sn/Zn/TiO_2$	AMX	Visible Light	67	12	135

Notes: Amoxicillin - AMX; Ultraviolet - UV. **Table Credit:** Pandurangan Vijayalakshmi.

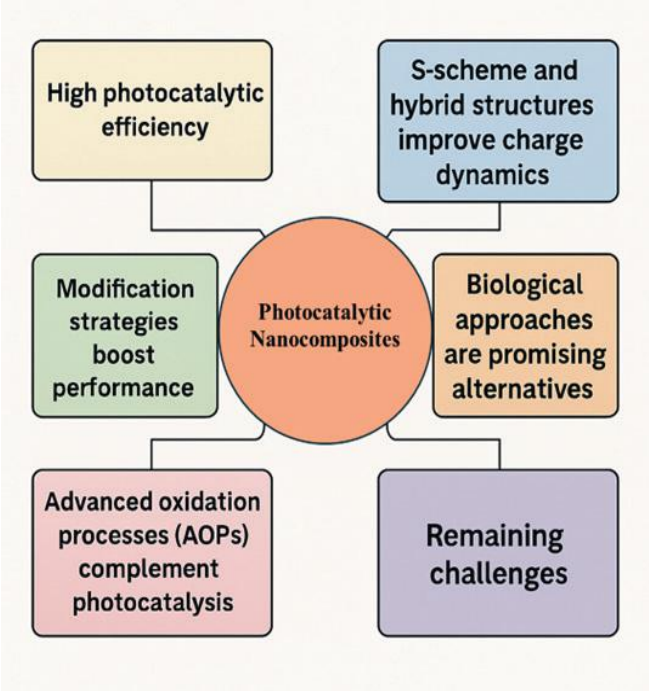

Figure 7. The key findings of the overall process
Image Credit: Pandurangan Vijayalakshmi.

CONCLUSION

This review highlights recent advancements in photocatalytic nanocomposites for the efficient degradation of amoxicillin (AMX) in wastewater treatment. The superior photocatalytic performance of materials such as mesoporous carbon nitride (MCN), TiO_2 nanoparticles, sulfur-doped $C_3N_5/DyFeO_3$, $BiVO_4$, and MXene-based composites demonstrates their potential in antibiotic removal with minimal byproduct toxicity. Integrating advanced strategies, including heterostructure formation, elemental doping, and biosynthesized nanoparticles, has significantly enhanced photocatalytic activity, with MXene-based systems achieving up to 99% AMX degradation efficiency. Additionally, incorporating S-scheme heterojunctions and hybrid photocatalytic systems, such as $Cs_3PMo_{12}O_{40}/MnIn_2S_4$, has improved charge separation and interfacial interactions, further boosting degradation efficiency. Beyond photocatalysis, advanced oxidation processes (AOPs), including UV/chloramine and ozonation, offer additional pathways for pharmaceutical pollutant degradation while minimizing secondary pollution. Biological remediation approaches, such as Trametes versicolor fungi for cytostatic drug detoxification, present sustainable and eco-friendly alternatives. While significant progress has been made, challenges, including photocatalyst stability, scalability, and cost-effectiveness, must be addressed to facilitate real-world applications. Future research should optimize photocatalyst design, explore synergistic treatment approaches, and evaluate long-term environmental impacts. By advancing nanocomposite-based photocatalysis, this field can contribute to developing more sustainable and effective wastewater treatment technologies, ultimately mitigating the risks associated with pharmaceutical contaminants within aquatic ecosystems.

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Consent for Publication

The author reviewed and approved the final version and has agreed to be accountable for all aspects of the work, including any accuracy or integrity issues.

DISCLOSURE

The author declares that they do not have any financial involvement or affiliations with any organization, association, or entity directly or indirectly related to the subject matter or materials presented in this review paper. This includes honoraria, expert testimony, employment, ownership of stocks or options, patents, or grants received or pending royalties.

Data Availability

Information for this review paper is taken from freely available sources.

Authorship Contribution

All authors contributed significantly to the work, whether in the conception, design, utilization, collection, analysis, and interpretation of data or all these areas. They also participated in the paper's drafting, revision, or critical review, gave their final approval for the version that would be published, decided on the journal to which the article would be submitted, and made the responsible decision to be held accountable for all aspects of the work.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval

Not applicable.

Use of Artificial Intelligence (AI) Tools

Not Applicable

Use of Research Reporting Tool

Not Applicable.

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