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Review

A Review of Visible-Light-Active Zinc Oxide Photocatalysts for Environmental Application

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Abstract: Zinc oxide (ZnO) photocatalysts have emerged as a promising material for environmental and energy applications due to their exceptional photocatalytic properties. Initially recognized for their efficiency under ultraviolet (UV) light, recent advancements have focused on enhancing ZnO's visible light activity (VLA) to address its inherent limitations. This review provides an overview of ZnO's structure, electronic properties, and photocatalytic mechanisms. Various strategies for modifying ZnO to harness visible light, including metal and non-metal doping, dye sensitization, and semiconductor coupling, are discussed. Special emphasis is placed on the mechanisms behind visible light absorption and reactive oxygen species (ROS) generation, as deduced through physicochemical and photoelectrochemical analyses. The applications of ZnO in environmental remediation are comprehensively explored, particularly for water treatment, disinfection, and air purification. The photocatalytic degradation of pollutants, including persistent organic compounds, pharmaceuticals, dyes, and pesticides, using ZnO is reviewed and compared with conventional UV-activated ZnO materials. This review underscores the potential of ZnO as an efficient and sustainable solution for environmental purification.

Keywords: zinc oxide (ZnO); visible light photocatalysis; water treatment; air purification; organic pollutant degradation

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1. Introduction

1.1. Structural Outline of ZnO

Zinc oxide (ZnO) is a semiconductor material with a wide band gap, typically around 3.37 eV, and a high exciton binding energy of nearly 60 meV. These properties make it suitable for various applications, including optoelectronics and photocatalysis. Recent studies have focused on modifying ZnO's structural and electronic characteristics to enhance its performance in these areas. One approach involves doping ZnO with transition metals to alter its electrical and magnetic properties. For instance, titanium ion implantation into ZnO films has been shown to tailor their electrical and magnetoelectric transport properties, potentially improving their suitability for electronic devices [1]. Another study explored the effects of chloride ion doping on ZnO nanostructures. The research demonstrated that varying chloride ion concentrations can significantly enhance the photocatalytic degradation efficiency of methylene blue in both alkaline and acidic media, indicating potential applications in environmental remediation [2]. Additionally, the physical and electronic properties of ZnO have been investigated using first-principles density functional theory. This theoretical study provided insights into how different computational methods, such as LDA (GGA) and LDA (GGA) +U, affect the predicted properties of ZnO, contributing to a deeper understanding of its behavior at the atomic level [3]. Furthermore, the synthesis of silver-doped ZnO nanoparticles has been achieved through efficient room-temperature methods. These nanoparticles exhibit unique structural and optical properties, along with enhanced photocatalytic activity, making them efficient materials for applications in environmental clean-up and antibacterial uses [4]. Lastly, the influence of stacking order on the physical and optical properties of Cu_2ZnSnS_4 absorber layers, prepared from DC-sputtered oxygenated precursors, has been studied. This research provides valuable information on how structural modifications can impact the performance of materials used in photovoltaic applications [5].

This review article presents a comprehensive evaluation of visible-light-active zinc oxide (ZnO) photocatalysts, emphasizing their environmental applications. While previous studies have explored ZnO-based materials, this review distinguishes itself by systematically addressing recent advancements in doping strategies, heterojunction formations, and morphological modifications aimed at enhancing visible light activity. For instance, the development of ZnO-based heterojunctions has shown significant promise in improving photocatalytic efficiency under visible light [6]. Additionally, the incorporation of dopants has been demonstrated to enhance the degradation of emerging pollutants [7]. For instance the incorporation of Selenium in the Zinc oxide structure may change its properties dramatically, as shown in Figure 1. By connecting material design strategies with practical environmental applications, such as pollutant degradation and water treatment, this study offers a unique perspective that bridges fundamental research and real-world implementation. To the best of our knowledge, this is among the few reviews to comprehensively focus on recent innovations in visible-light-responsive ZnO photocatalysts tailored for environmental remediation.

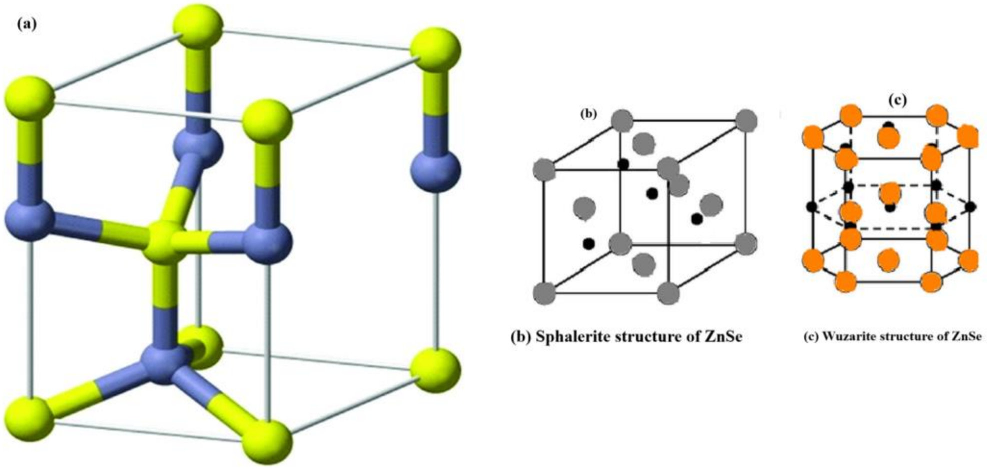

Figure 1. (**a**) Crystalline structure of zinc oxide (ZnO) (**b**) Sphalerite structure of ZnSe, (**c**) wurtzite structure of ZnSe [8,9].

1.2. Motivation for Visible Light Activation of ZnO

Zinc oxide (ZnO) is a semiconductor with a wide band gap of approximately 3.37 eV, which restricts its photocatalytic activity to the ultraviolet (UV) region of the spectrum. This limitation has prompted extensive research aimed at modifying ZnO to enable activation under visible light, thereby expanding its potential for environmental remediation and energy conversion. One promising approach involves doping ZnO with non-metal elements to narrow its band gap. For example, nitrogen doping has been shown to introduce mid-gap states, facilitating visible light absorption and significantly enhancing the photocatalytic efficiency in degrading organic pollutants [10]. Another strategy is the formation of heterojunctions by coupling ZnO with other semiconductors. For instance, a study demonstrated that combining ZnO with cadmium sulfide (CdS) forms a Z-scheme heterojunction, which enhances charge separation under visible light, leading to improved photocatalytic performance [11]. Additionally, surface modification techniques, such as the incorporation of plasmonic nanoparticles, can enhance light absorption. For example, gold nanoparticles can induce localized surface plasmon resonance, significantly boosting ZnO's photocatalytic activity under visible light [10].

1.3. Scope of ZnO Particles and Their Environmental Impact

Zinc oxide (ZnO) nanoparticles have garnered significant interest due to their unique properties and diverse applications, particularly in environmental contexts. Their photocatalytic capabilities make them highly effective in degrading organic pollutants, providing promising solutions for wastewater treatment and air purification [12]. Additionally, ZnO nanoparticles exhibit antimicrobial properties, making them effective in controlling pathogenic microorganisms in various environmental settings [13]. However, the increasing use of ZnO nanoparticles raises concerns about their environmental impact. Studies have shown that these nanoparticles can adversely affect aquatic ecosystems. For example, exposure to ZnO nanoparticles has been associated with toxicity in algae, leading to disruptions in photosynthesis and growth [14]. Furthermore, ZnO nanoparticles can interact with soil components, potentially altering soil chemistry and impacting microbial communities that are essential for nutrient cycling [15]. To mitigate these environmental risks, research is focusing on developing eco-friendly synthesis methods and exploring the behavior and performance of ZnO nanoparticles in natural environments. Understanding their interactions with environmental matrices is crucial for assessing their long-term impact and guiding the development of safer nanomaterials [15].

1.4. Overview of ZnO Particles' Photocatalytic Properties and Relevance of Their Environmental Application

Recent studies on zinc oxide (ZnO) nanoparticles have highlighted their strong photocatalytic properties, making them effective in environmental applications such as pollutant degradation. ZnO's unique photocatalytic ability arises from its capacity to absorb UV light and generate reactive oxygen species, such as hydroxyl radicals, which can effectively degrade organic pollutants in water. For instance, when combined with activated carbon, ZnO significantly enhances the adsorption and photodegradation of pollutants, such as phenol, achieving high removal rates under UV light [16]. This hybrid material not only improves pollutant breakdown but also regenerates, allowing for multiple uses in pollutant treatment systems [16]. Various doping techniques further enhance ZnO's efficiency under solar irradiation. For example, carbon-, nitrogen-, and sulfur-doped ZnO nanoparticles exhibit improved absorption of the visible spectrum of light and have achieved notable degradation efficiencies in dye removal tests, with sulfur-doped ZnO reaching up to 81.4% degradation efficiency under UV light. These doping strategies reduce the material's band gap, thereby enhancing its photocatalytic activity under visible light [17]. Laser ablation methods have also been explored to produce ZnO with specific shapes and surface defects, optimizing the material's photocatalytic efficiency. ZnO nanorods, produced through laser ablation in water, show superior photocatalytic performance compared to spherical nanostructures, largely due to an increased surface defect density. This makes ZnO nanorods particularly effective for applications where rapid pollutant degradation is required [18].

Figure 2 illustrates the photocatalytic mechanism of zinc oxide nanoparticles (ZnO NPs). When ZnO NPs absorb photons with energy greater than their band gap (~2.9 eV), electrons (e^-) are excited from the valence band to the conduction band, leaving behind holes (h^+) in the valence band. These excited electrons reduce oxygen (O_2) to form superoxide radicals ($\bullet O_2^-$), while the holes oxidize water molecules (H_2O) to generate hydroxyl radicals (•OH). Both $\bullet O_2^-$ and •OH are highly reactive species that degrade methylene blue into harmless byproducts such as water (H_2O), carbon dioxide (CO_2), and inorganic acids over a period of 240 min. The molecular orbital diagram of MB, showing the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO), highlights the interaction with the photocatalytically active species, leading to efficient dye degradation.

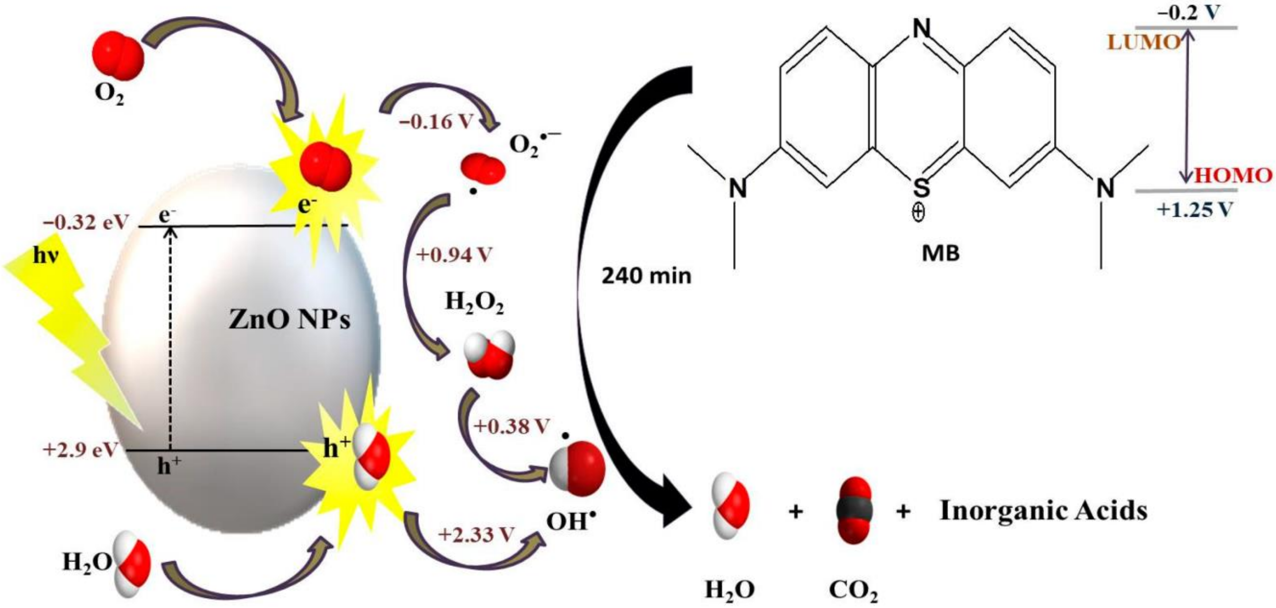

Figure 2. Photocatalytic mechanism of ZnO-NPs [19].

2. ZnO Structures and Photocatalytic Properties

2.1. Types of ZnO Structures and Their Properties

Zinc oxide (ZnO) nanostructures exhibit diverse morphologies, each imparting unique properties that influence their suitability for various applications. Recent studies have explored these structures extensively, highlighting their distinct characteristics and potential uses. These are discussed below.

Nanoparticles: Nanoparticles are spherical structures, typically ranging from a few to several hundred nanometers in size. Their high surface area-to-volume ratio enhances photocatalytic activity, making them effective in degrading organic contaminants under UV light [20]. Additionally, their antimicrobial properties are leveraged in biomedical applications, such as antibacterial coatings and drug delivery systems.

Nanorods: Nanorods are elongated structures with high aspect ratios, providing directional charge transport properties. This makes them appropriate for application in optoelectronic strategies, including light-emitting diodes and photo sensors [21]. Their anisotropic shape also facilitates enhanced electron mobility, beneficial for sensor applications [22].

Nanosheets: Nanosheets are two-dimensional structures with large surface areas and thin profiles. These characteristics contribute to superior gas sensing capabilities due to increased surface adsorption sites [23]. Their unique morphology also enhances photocatalytic efficiency in environmental remediation processes [20].

Nanowires: One-dimensional nanowires may have lengths of multiple micrometers and have diameters in the nanometer range. Their high crystallinity and exterior surfaces make them ideal for use in piezoelectric nanogenerators and field-effect transistors [21]. The high aspect ratio of nanowires facilitates efficient charge separation, enhancing their performance in photovoltaic devices [22]. The physical and structural properties of Wurtzite and Sphalerite ZnO are summarised in Table 1.

Table 1. Physical and structural properties of ZnO (Wurtzite & Sphalerite).

Property	**Wurtzite ZnO**	**Sphalerite ZnO**
Crystal system	Hexagonal	Cubic (Zinc Blende)
Coordination number	Tetrahedral (each Zn and O atom is coordinated with four atoms)	Tetrahedral
Lattice Parameters	a ≈ 3.25 Å, c ≈ 5.2 Å	a ≈ 4.62 Å
Stability	Thermodynamically stable at ambient conditions	Metastable; forms under specific conditions
Physical properties	Piezoelectric and pyroelectric	Centrosymmetric; lacks piezoelectricity
Electronic Bandgap	≈3.37 eV	Slightly similar (depends on preparation)
Application	Sensors, optoelectronic devices, catalysts	Rare; specialized conditions

2.2. Photocatalytic Mechanism Under UV and Visible Light

Zinc oxide (ZnO) is a semiconductor renowned for its photocatalytic properties, which are primarily activated under ultraviolet (UV) light due to its wide band gap of approximately 3.37 eV. Upon UV illumination, electrons are promoted from the valence band to the conduction band and electron–hole pairs are created when ZnO absorbs photons with energy equal to or greater than its band gap. These charge carriers can initiate redox reactions, leading to the degradation of organic pollutants [24]. However, ZnO's limited absorption in the visible spectrum restricts its photocatalytic efficiency under visible light. To report this, different strategies have been engaged to extend ZnO photo response into the visible range. One approach involves doping ZnO with non-metal elements, such as nitrogen or carbon, which introduces impurity levels within the band gap, leading to visible light captivation and enhanced photocatalytic activity [25]. Another method is the formation of heterojunctions by coupling ZnO with fine band gap semiconductors like cadmium sulfide (CdS). This combination facilitates efficient charge separation and broadens the light absorption spectrum, thereby improving photocatalytic performance under visible light [11]. Additionally, surface modification with noble metals, such as silver or gold, can improve visible light photocatalysis. These metals induce localized surface plasmon resonance, increasing light captivation and promoting charge carrier parting, which collectively boosts the photocatalytic efficiency of ZnO [26].

2.3. Band Gap Properties and Absorption Characteristics of ZnO

Zinc oxide (ZnO) is a semiconductor characterized by a wide direct band gap of roughly 3.37 eV at room temperature, corresponding to an absorption edge near 375 nm in the ultraviolet (UV) region. This band gap enables ZnO to absorb UV light effectively, making it suitable for applications such as UV photodetectors and photocatalysts [27] However, ZnO's limited absorption in the visible spectrum restricts its utility in applications requiring visible light activation. To state this restriction, many strategies have been introduced to modify the ZnO band gap and enhance its absorption characteristics. Doping with non-metal elements: Incorporating non-metal dopants like nitrogen or carbon into ZnO introduces impurity levels within the band gap, effectively narrowing it and enabling the absorption of visible light. This modification enhances ZnO photocatalytic activity under visible light irradiation, broadening its applicability in environmental remediation [28]. Formation of heterojunctions: Combining ZnO with narrow band gap semiconductors, such as cadmium sulfide (CdS), forms heterojunctions that facilitate efficient charge separation and encompass light absorption into the detectable array. This approach improves photocatalytic performance under visible light, making ZnO-based composites more effective in degrading organic pollutants. Surface modification with noble metals: Depositing noble metals like silver or gold onto ZnO surfaces induces localized surface plasmon resonance, enhancing light absorption and promoting charge carrier separation. This modification increases ZnO photocatalytic efficiency under visible light, expanding its potential applications in environmental and energy-related fields [29].

2.4. Modification Strategies to Expand the Light Absorption of ZnO

ZnO having a band gap of approximately 3.2 eV exhibits photocatalytic activity mainly under UV light of wavelength less than 388 nm. This limits application under visible light, which comprises a large part of the solar spectrum. Various modification strategies have been developed to extend the absorption of ZnO to the visible range and improve its efficiency in environmental applications.

2.4.1. Modification Strategies for Visible Light Activation

Metal and Non-Metal Doping

Doping ZnO with elements such as Ag, Fe, N, and S introduces mid-gap states or reduces the bandgap, enabling the absorption of visible light. For instance, nitrogen doping creates shallow acceptor levels, while silver doping introduces plasmonic effects that enhance light absorption [30–32].

Coupling with Narrow Bandgap Semiconductors

The formation of heterojunctions with materials like $BiVO_4$, g-C_3N_4, or CdS not only extends the absorption range but also promotes efficient charge separation, reducing recombination losses. This synergistic interaction enhances the overall photocatalytic performance [33–35].

Surface Sensitization with Plasmonic Nanoparticles

Sensitizing ZnO with plasmonic materials such as Au or Ag nanoparticles generates localized surface plasmon resonance (LSPR), which amplifies visible light absorption and facilitates hot electron injection into ZnO’s conduction band [36,37].

Morphology Engineering

The distinctive architectures of ZnO, such as nanorods, nanowires, and nanosheets, have a significant influence on light absorption and charge separation. These nanostructures facilitate guided electrical conduction and provide an enlarged surface for catalytic activities [38].

Mechanistic Insights

Each modification technique uses a different mechanism to increase visible light activity. For instance, metal doping changes the electronic structure of ZnO, resulting in defect states that make it easier for visible light to be absorbed. As opposed to plasmonic sensitizers, which use LSPR to boost photon energy harvesting, heterojunctions improve interfacial charge transfer [39].

3. Methods for Enhancing ZnO Photocatalytic Efficiency

3.1. Non-Metal Doping of ZnO

Non-metal doping of zinc oxide (ZnO) involves introducing elements such as nitrogen (N), carbon (C), or sulfur (S) into the ZnO lattice to modify its electronic and optical properties. This process aims to enhance ZnO photocatalytic efficiency, particularly under visible light irradiation, thereby broadening its applicability in environmental remediation and energy conversion.

3.1.1. Role of Non-Metals Such as Nitrogen, Carbon, and Sulfur

Nitrogen Doping:

Incorporating nitrogen into ZnO introduces impurity levels within the band gap, effectively narrowing it and enabling the absorption of visible light. This modification enhances ZnO photocatalytic activity under visible light irradiation, broadening its applicability in environmental remediation [40]. The photocatalytic mechanism of nitrogen-doped zinc oxide (N-doped ZnO) for dye degradation under UV light is shown in Figure 3. N-doped ZnO absorbs photons with energies equal to or higher than its band gap when exposed to UV light. The valence band (VB) has positive holes (h^+) left behind after electrons (e^-) in the VB jump to the conduction band (CB) because of this excitation. Nitrogen doping increases visible light absorption and boosts charge carrier separation efficiency by introducing new energy levels into the band gap.

Carbon Doping: Carbon doping of ZnO has been shown to create isolated states above the valence band maximum, enhancing visible light absorption. Theoretical calculations support these findings, indicating that carbon-doped ZnO exhibits improved photocatalytic performance under visible light [41].

Sulfur Doping: Sulfur doping introduces impurity states within the band gap, facilitating visible light absorption and enhancing photocatalytic activity. Studies have demonstrated that sulfur-doped ZnO exhibits improved filth of organic impurities under visible light sterilization [40].

Figure 3. Doping of transition metals like carbon, sulfur and nitrogen [42].

3.1.2. Impact on Light Absorption and Catalytic Efficiency

Non-metal doping of zinc oxide (ZnO) significantly enhances its light absorption capabilities and catalytic efficiency, particularly under visible light irradiation. This modification is crucial for broadening ZnO applicability in environmental remediation and energy conversion.

Enhanced Light Absorption: Coupling ZnO with semiconductors that have narrower band gaps, such as g-C_3N_4, extends the light absorption series into the visible spectrum.

This broadens the photocatalytic response, making the composite materials more effective under sunlight [43].

Improved Catalytic Efficiency: The synergistic effect of combining ZnO with other semiconductors results in composites with superior photocatalytic properties compared to individual components. For example, ZnO/TiO_2 heterojunctions have shown enhanced degradation rates of organic pollutants due to improved charge transfer dynamics [44].

3.1.3. Effects of Transition Metals Like Fe and Cu on ZnO Photocatalysis

Iron (Fe) Doping:

Incorporating non-metal fundamentals such as nitrogen (N), carbon (C), or sulfur (S) into the ZnO lattice introduces impurity states within the band gap. These states effectively narrow the band gap, enabling ZnO to absorb visible light. For instance, nitrogen doping has been shown to shift the absorption edge of ZnO into the visible region, thereby enhancing its photocatalytic activity under visible light [45].

Copper (Cu) Doping:

Cu doping of ZnO enhances visible light absorption by introducing impurity levels within the band gap, effectively narrowing it. This modification allows ZnO to utilize a broader spectrum of light for photocatalysis. Studies have reported that Cu-doped ZnO nanocomposites exhibit 100% photocatalytic degradation of methylene blue under sunlight irradiation within 60 min, with excellent stability over multiple cycles [46]. Furthermore, Cu-doped ZnO/Ag/CuO heterostructures have demonstrated superior photocatalytic performance and charge transfer properties, ascribed to the synergistic effects of doping and heterojunction formation [47].

3.2. ZnO–Semiconductor Composites

3.2.1. Benefits of Coupling ZnO with Other Semiconductors (e.g., TiO_2, g-C_3N_4) for Enhanced Charge Separation

Coupling zinc oxide (ZnO) with other semiconductors, such as titanium dioxide (TiO_2) and graphitic carbon nitride (g-C_3N_4), has been extensively studied to enhance photocatalytic performance. This strategy aims to improve charge separation, extend light absorption, and increase overall efficiency in photocatalytic applications.

Enhanced Charge Separation: Forming heterojunctions between ZnO and other semiconductors enables efficient separation of photogenerated electron–hole pairs, dropping recombination rates. For instance, ZnO/g-C_3N_4 heterojunctions have demonstrated improved charge carrier separation, leading to heightened photocatalytic action under visible light irradiation [48]. Figure 4 illustrates the mechanism of charge transfer in a g-C_3N_4/ZnO heterojunction. (a) Before contact, g-C_3N_4 and ZnO exhibit different Fermi levels (F_1 and F_2) due to their distinct band structures. (b) Upon contact, a built-in electric field forms at the heterojunction interface as electrons flow from ZnO (higher Fermi level) to g-C_3N_4 (lower Fermi level) until equilibrium is reached. This electric field aids in charge separation. (c) Under light irradiation, both materials absorb photons, generating electron–hole pairs. The built-in electric field drives electrons toward g-C_3N_4 and holes toward ZnO, effectively separating charges and enhancing photocatalytic performance.

Extended Light Absorption: Coupling ZnO with semiconductors that have narrower band gaps, such as g-C_3N_4, extends the light absorption series into the visible spectrum. This broadens the photocatalytic response, making the composite materials more effective under sunlight [43].

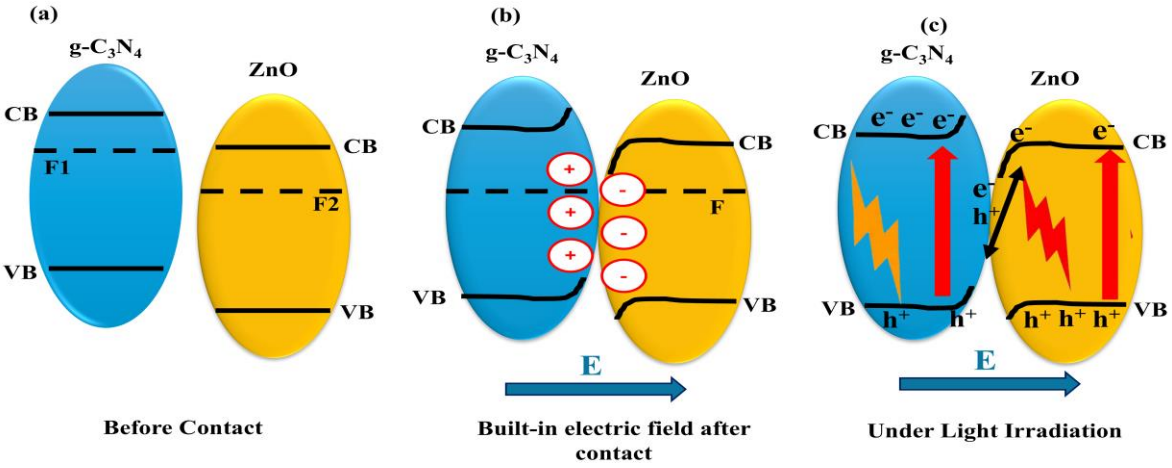

Figure 4. Doping of ZnO with g-C_3N_4 (Linley and Thomson, 2021) [49].

Improved Photocatalytic Performance: The synergistic effect of combining ZnO with other semiconductors results in composites with superior photocatalytic properties compared to individual components. For example, ZnO/TiO_2 heterojunctions have shown enhanced degradation rates of organic pollutants due to improved charge transfer dynamics [44]. In Figure 5, the photocatalytic mechanism of a ZnO/TiO_2 heterojunction under sunlight is demonstrated. Both ZnO and TiO_2 absorb UV light, generating electron–hole pairs. When ZnO absorbs light, electrons (e^-) in its valence band (VB) are excited to its conduction band (CB), leaving behind holes (h^+) in the VB. Similarly, TiO_2 undergoes the same process. Due to the staggered alignment of their energy levels, electrons from the CB of ZnO transfer to the CB of TiO_2, while holes from the VB of TiO_2 move to the VB of ZnO. This bidirectional charge transfer effectively separates the photogenerated electrons and holes, reducing recombination and enhancing photocatalytic activity. The synergistic interaction between ZnO and TiO_2 makes the heterojunction highly effective for environmental and energy applications, such as pollutant degradation and water splitting.

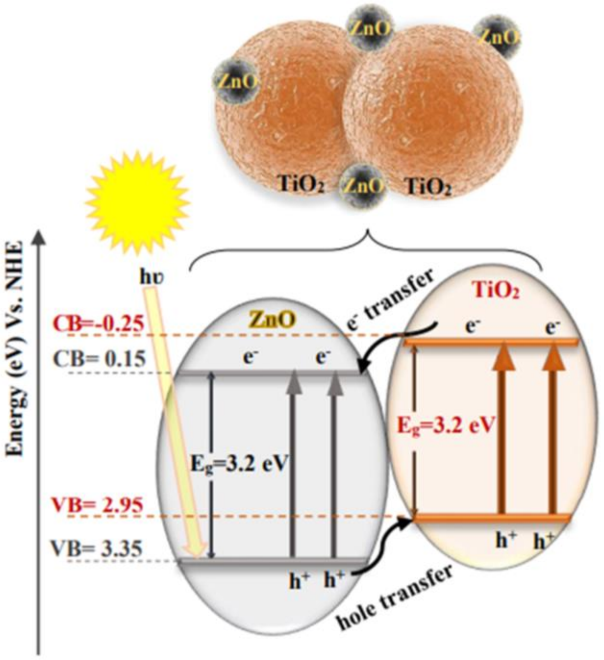

Figure 5. Doping of ZnO with TiO_2 [50].

3.2.2. Mechanisms of Photocatalytic Action in ZnO

Zinc oxide (ZnO) is a widely studied photocatalyst owing to its unique electronic structure and environmental applications. The photocatalytic mechanism of ZnO involves several key steps:

3.2.3. Key Pathways in the Photocatalytic Degradation of Pollutants by ZnO

Charge Carrier Separation and Migration:

The photogenerated electrons and holes can either recombine, releasing energy as heat or light, or migrate to the surface of the ZnO particle. Resourceful separation and migration of these charge carriers are crucial for effective photocatalysis [51].

Formation of Reactive Oxygen Species (ROS):

Oxidation Reactions: Strong oxidative potential permits the valence band holes to oxidize water molecules and hydroxide ions deposited on the ZnO surface, producing hydroxyl radicals (OH). These highly reactive radicals are crucial to the breakdown of organic contaminants [52].

Reduction Reactions: The electrons in the conduction band can reduce molecular oxygen adsorbed on the ZnO surface to form superoxide anions ($O_2{}^{-\bullet}$). These anions can further react to produce other ROS, such as hydrogen peroxide (H_2O_2), contributing to the oxidative degradation processes [53].

Degradation of Pollutants: The ROS generated through these mechanisms are highly efficient at transforming intricate chemical molecules into less hazardous and simpler ones, making ZnO a valuable photocatalyst for environmental remediation applications [54]. Doping ZnO with transition metals like iron (Fe) has been shown to improve charge separation and increase the production of ROS, thereby enhancing photocatalytic performance [55]. In Figure 6, the detoxification mechanism for the degradation of antibiotics has been demonstrated using zinc oxide as catalyst.

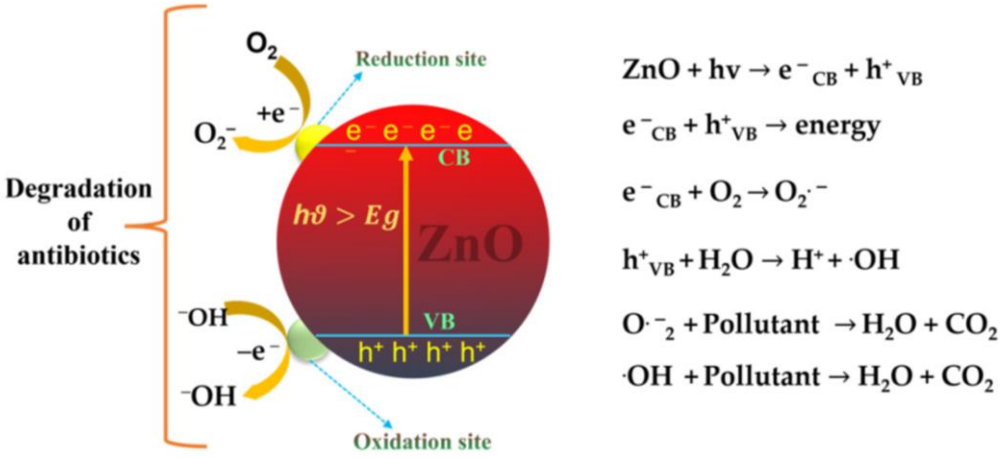

Figure 6. ZnO detoxification mechanism of pollutants (Mohamed, Benitto, Vijaya, and Bououdina, 2023) [56].

4. Applications of Visible-Light-Active ZnO Photocatalysts

In recent years, zinc oxide (ZnO) has attracted a lot of attention due to its effectiveness in cleaning water and breaking down organic contaminants. It is a potential material for environmental remediation because of its photocatalytic qualities, which allow the breakdown of complex organic molecules and the inactivation of microbiological pollutants.

4.1. Water Treatment and Purification

Application of ZnO in Degrading Organic Pollutants and Disinfecting Water

Degradation of Organic Pollutants:

The breakdown of various organic contaminants, such as dyes, drugs, and pesticides, is facilitated by ZnO photocatalytic activity. When exposed to light, ZnO releases reactive oxygen species (ROS), which oxidize and break down these pollutants into safer forms. For instance, under UV light irradiation, ZnO-based photocatalysts have demonstrated high efficiency in degrading methylene blue dye [57]. As discussed in Table 2, the various preparation methods and their efficiencies for practical use are outlined. Additionally, ZnO nanostructures have been successfully employed to degrade emerging contaminants, further showcasing their versatility in water treatment applications [45].

Table 2. ZnO photocatalyst synthesis and photocatalytic activity.

ZnO Morphology	Synthesis Method	Target Contaminants	Removal Efficiency	Experimental Condition	Reference
Nanowires	Hydrothermal	Methylene Blue (MB)	86% after 180 min	UV irradiation	[58]
Nanowires	Hydrothermal	Methyl Orange (MO)	49% after 180 min	UV irradiation	[58]
Nanowires	Hydrothermal	Acid Red 14 (AR14)	93% after 180 min	UV irradiation	[58]
ZnO/Cu-DPA Composite	Co-precipitation	Methylene Blue (MB)	87% within 80 min	Visible light irradiation	[59]
ZnO Nanoparticles	Precipitation	Methylene Blue (MB)	96.5%	Direct sunlight irradiation	[60]
ZnO/PVP Nanoparticles	Sol-gel	Industrial dye wastewater	Significant degradation	UV irradiation	[61]
Porous ZnO Coral-like Nanoplates	Wet-chemical	Methylene Blue (MB)	Enhanced efficiency	UV irradiation	[62]
ZnO/Activated Carbon Composite	Co-precipitation	Acid Green 25 (AG25)	Faster degradation	UV irradiation	[63]
ZnO Nanoparticles	Green synthesis	Various organic dyes	Effective degradation	UV irradiation	[64]

Water Disinfection:

Beyond pollutant degradation, ZnO exhibits antimicrobial properties, making it effective in water disinfection. The ROS generated during photocatalysis can inactivate bacteria and viruses, contributing to improved water quality. Studies have reported the successful application of ZnO nanostructures in bacterial disinfection, highlighting their potential to address microbial contamination in water sources [65].

4.2. Air Purification and VOC Removal

Use of ZnO for the Breakdown of Airborne Pollutants and Volatile Organic Compounds (VOCs)

Zinc oxide (ZnO) has reaped noteworthy consideration in recent years for its efficacy in degrading airborne pollutants and volatile organic compounds (VOCs). Its photocatalytic properties enable the breakdown of complex organic compounds, making it an auspicious fact for environmental remediation.

Photocatalytic Degradation of VOCs:

ZnO photocatalytic activity facilitates the degradation of various VOCs, including formaldehyde, benzene, and toluene. Upon exposure to light, ZnO produces reactive oxygen species (ROS) that oxidize and decompose these contaminants into less harmful substances. For instance, ZnO-based photocatalysts have demonstrated high efficiency in degrading formaldehyde under UV light irradiation [66]. Additionally, ZnO nanostructures have been employed to degrade benzene and toluene, showcasing their versatility in air purification applications [17].

Enhancements through Doping and Composite Formation:

To improve ZnO photocatalytic performance, researchers have explored doping with metal and non-metal elements, as well as forming composites with other semiconductors. These modifications aim to enhance visible light absorption and charge separation efficiency. For example, doping ZnO with elements like nitrogen has been shown to extend its light immersion into the visible spectrum, thereby increasing its photocatalytic activity under sunlight. Similarly, coupling ZnO with materials such as $NiFe_2O_4$ has resulted in composites with superior photocatalytic properties, demonstrating improved degradation rates of VOCs. ZnO-based photocatalysts have been integrated into various air purification systems to effectively remove VOCs and other airborne pollutants. These systems utilize ZnO photocatalytic properties to degrade contaminants, resulting in cleaner indoor air quality [58]. The development of ZnO-based nanomaterials with enhanced surface areas and reactivity has further improved the efficiency of these air purification systems [67].

4.3. Photocatalytic Hydrogen Production

ZnO Role in Water Splitting for Hydrogen Generation and Clean Energy

Zinc oxide (ZnO) has garnered significant attention in recent years for its potential in photocatalytic water splitting, a process that generates hydrogen—a clean and sustainable energy carrier. The unique properties of ZnO, such as its suitable band gap and high electron mobility, make it a promising candidate for this application.

Photocatalytic Water Splitting Mechanism:

ZnO absorbs photons, which excites electrons from the valence band to the conduction band. Electron–hole pairs occur through this mechanism and are crucial for further redox reactions: while the holes oxidize water molecules to make oxygen, the photogenerated electrons assist in the loss of protons to produce hydrogen gas [68].

Challenges and Strategies for Enhancement:

Despite its potential, ZnO faces challenges such as swift recombination of electron–hole pairs and inadequate absorption in the visible light spectrum. To address these concerns, numerous policies have been employed:

Doping with Non-Metal Elements: Incorporating elements like nitrogen into the ZnO lattice can introduce new energy levels, narrowing the band gap and enhancing visible light absorption [69].

Formation of Heterostructures: Coupling ZnO with other semiconductors, such as cadmium sulfide (CdS), can facilitate efficient charge separation and extend light absorption into the visible range, thereby improving photocatalytic performance [70].

Morphological Control: Synthesizing ZnO in various nanostructures, like nanorods or nanosheets, surges the outward area and offers extra active sites for photocatalytic reactions, enhancing hydrogen production efficiency [71].

4.4. Protocols for Assessing the Photocatalytic Performance of ZnO Under Visible Light

Preparation of ZnO Photocatalyst:

Synthesis Methods: ZnO photocatalysts are synthesized using procedures such as hydrothermal synthesis, sol-gel processes, and chemical vapor deposition. These methods allow for control over unit magnitude, morphology, and doping planes, which are crucial for optimizing photocatalytic activity [72].

Doping and Composite Formation: To enhance visible light absorption, ZnO is often doped with elements like nitrogen or combined with other semiconductors to form heterostructures. These modifications aim to narrow the band gap and improve charge separation efficiency. In Table 3, a brief summary of ZnO heterojunction and their properties is given.

Table 3. A summary of ZnO heterojunctions and their properties.

Heterojunction	Materials Combined with ZnO	Key Benefits	Application
ZnO/TiO_2	Titanium Dioxide (TiO_2)	Enhanced charge separation and visible light response	Photocatalysis, solar cells
$ZnO/g\text{-}C_3N_4$	Graphitic Carbon Nitride ($g\text{-}C_3N_4$)	Increased photocatalytic efficiency under visible light	Photocatalysis, hydrogen evolution
ZnO/CuO	Copper Oxide (CuO)	Narrowed band gap, improved light absorption	Photocatalysis, gas sensors
ZnO/Ag_2O	Silver Oxide (Ag_2O)	High photocatalytic efficiency and charge carrier mobility	Antibacterial activity, water purification
ZnO/Graphene	Graphene	High conductivity, increased charge carrier transport	Sensors, supercapacitors, photocatalysis
ZnO/CdS	Cadmium Sulfide (CdS)	Visible light absorption, improved photogenerated charge separation	Photo voltaic, photocatalysis
ZnO/Fe_2O_3	Hematite (Fe_2O_3)	Improved magnetic and photocatalytic properties	Magnetic materials, photocatalysis
ZnO/MoS_2	Molybdenum Disulfide (MoS_2)	Enhanced light absorption and carrier mobility	Photodetectors, solar energy conversion
ZnO/SnO_2	Tin Dioxide (SnO_2)	Enhanced sensitivity and response time for gas sensing	Gas sensors, photocatalysis
$ZnO/SrTiO_3$	Strontium Titanate ($SrTiO_3$)	High charge carrier separation and visible light activity	Photocatalysis, electronics

Characterization Techniques:

Structural Analysis: To ascertain the crystalline structure and phase purity of ZnO samples, X-ray diffraction (XRD) is utilized. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) shed light on the sizes and shapes of molecules [73]. The nanostructure size and morphology of zinc oxide (ZnO) vary significantly with the type of dopant and synthesis conditions. Vanadium (V)-doped ZnO typically exhibits a nanostructure size ranging from 10 to 50 nm below in Figure 7, whereas sulfur (S)-doped ZnO, on the other hand, usually has particle sizes between 20 and 80 nm, and lastly dysprosium (Dy)-doped ZnO often exhibits smaller sizes of 15 to 40 nm.

TEM images exhibit the morphology of a nanostructure. In Figure 7, the ZnO typically exhibits morphology including nanorods, nanoparticles, or nanosheets, influenced by lattice distortions introduced by vanadium ions. They form spherical or flower-like morphologies when doped with sulfur (c) and quasi-spherical or irregularly shaped nanoparticles when doped with dysprosium (d).

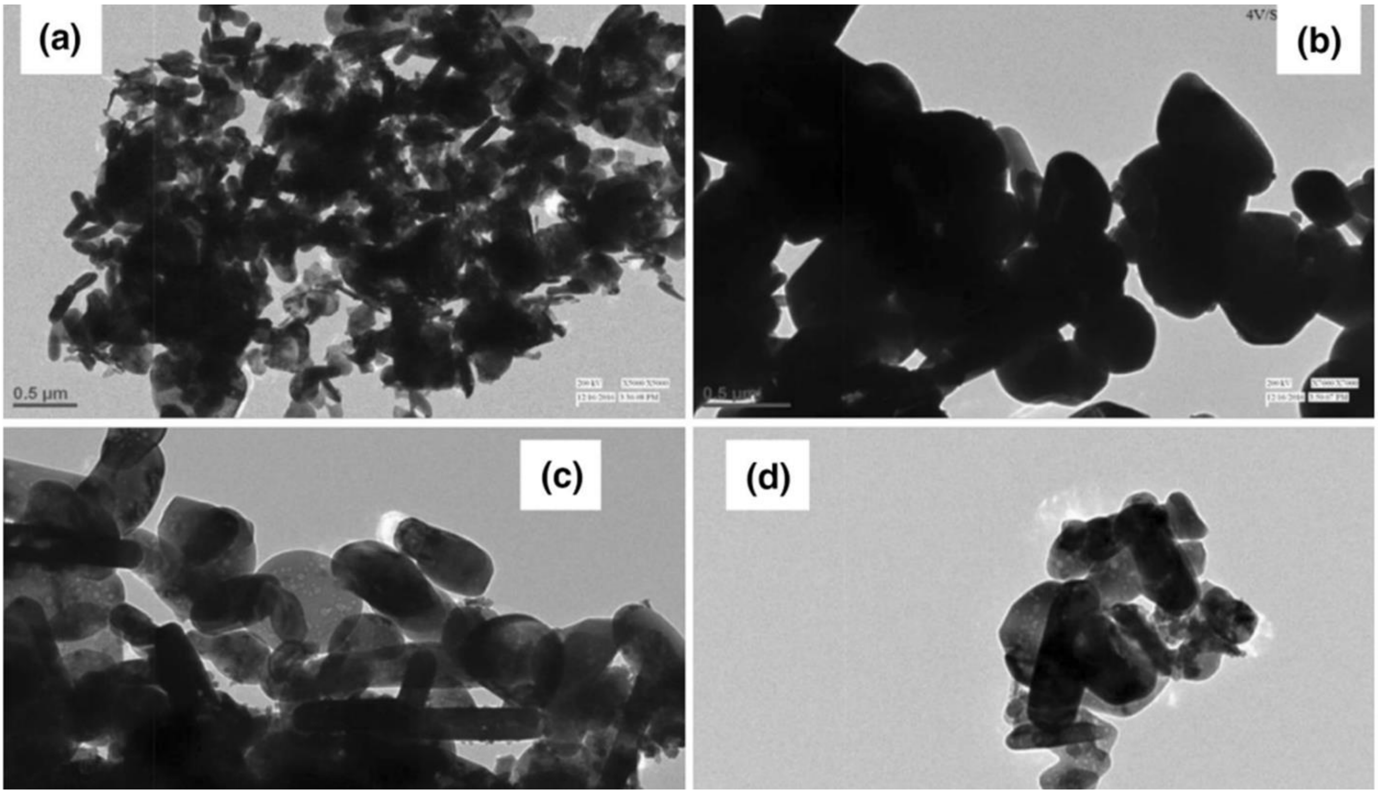

Figure 7. TEM images of (**a**) zinc oxide, (**b**) zinc oxide fixed by V, (**c**) zinc oxide incapacitated by S, and (**d**) Dy-nobbled ZnO nanoparticles [74].

The morphology of PVDF/functionalized PMMA/doped ZnO nanocomposites is shown in the SEM images in Figure 8. In Figure 8a, PVDF is uniformly blended with functionalized PMMA. Figure 8b depicts the uniform dispersion of V-doped ZnO nanoparticles (NS3) within the polymer matrix, with most particles of equal size. Similarly, Figure 8c shows S-doped ZnO nanoparticles with homogeneous shape and uniform distribution, deeply embedded in the matrix, displaying a luminescent effect likely attributed to the ZnO nanoparticles. This luminescence may vary depending on the dopant due to electron transitions. In Figure 8d, Dy-doped ZnO nanoparticles exhibit a rod-like morphology with less homogeneous distribution, possibly influenced by the Dy dopant.

Figure 9a, below explains the XRD patterns of ZnO and its doped forms sulfur (S), and providing insight into their crystalline structures and the effects of doping. Pure ZnO typically exhibits sharp peaks at 2θ values around 31.8°, 34.4°, and 36.3°, corresponding to the hexagonal wurtzite structure, indicating high crystallinity and purity. When doped with sulpher, slight shifts in peak positions are observed due to lattice distortion caused by the smaller ionic radius of S compared to Zn, and weak peaks of vanadium oxides may appear at higher doping levels. The peaks may broaden, indicating increased lattice strain or reduced crystallite size. FTIR spectroscopy in Figure 9b confirmed the formation of layered ZnO in the sulfur-doped sample and its microstructure evolution after RhB treatment. Features at 3000–3700 cm^{-1} relate to adsorbed H_2O and N–H vibrations from uncondensed amines. A slight band at 2130 cm^{-1} is attributed to RhB molecules. Thus, the transmittance of sulfur-doped ZnO shows no significant enhancement despite RhB adsorption. To study the recombination of photogenerated electron–hole pairs, photoluminescence (PL) spectra of the catalyst sheet were recorded (Figure 9c). Sulfur-doped ZnO showed a lower PL intensity than undoped ZnO, indicating suppressed recombination and enhanced charge carrier transport. Additionally, a redshift in emission peaks and a slight band gap decrease (from 2.7 eV to 2.57 eV) suggest improved visible light absorption and photocatalytic activity. Figure 9d shows the TG and DTA curves of sulfur-doped ZnO. The TG curve reveals three stages of weight loss between 30 °C and 550 °C, with significant decomposition and gas evolution occurring between 175 °C and 300 °C, leading to exothermic and endothermic peaks at 183 °C, 218 °C, and 247 °C. This process accounts for an 84.03% weight loss, with residual decomposition continuing slowly up to 550 °C.

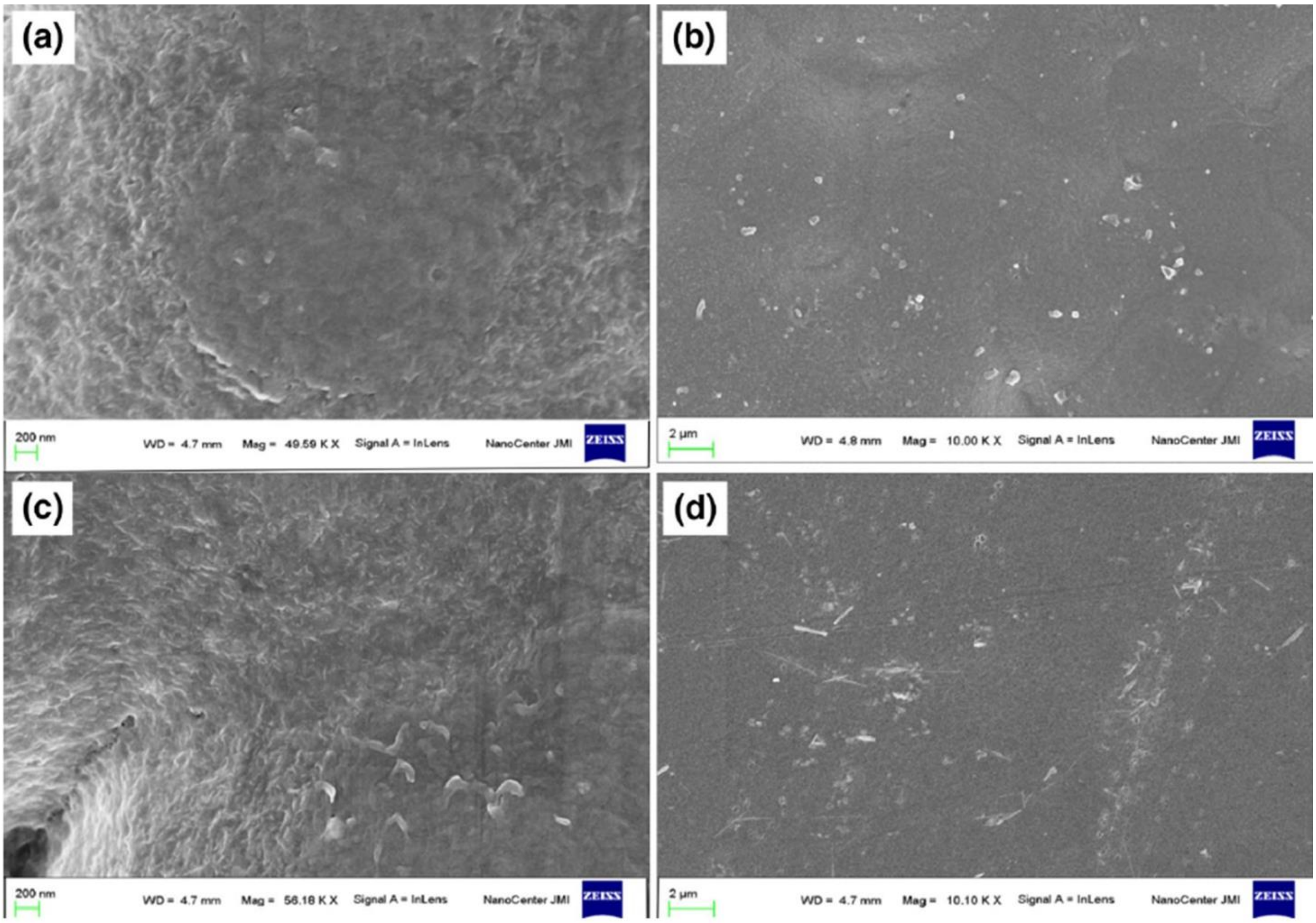

Figure 8. SEM Images of (**a**) zinc oxide, (**b**) V-tampered ZnO particles, (**c**) S-incapacitated ZnO, and (**d**) Dy-doped ZnO nanoparticles [74].

Photocatalytic Activity Evaluation:

Pollutant Degradation Tests: Monitoring the breakdown of organic dyes (such as methylene blue and rhodamine B) under exposure to visible light is a typical method of assessing photocatalytic performance. Using UV-Vis spectroscopy, the dye concentration reduction over time is quantified [66]. Figure 10 shows the photocatalytic degradation graph for rhodamine B dye. It typically demonstrates a gradual reduction in the dye's absorbance at its characteristic wavelength (around 553 nm) over time under visible light irradiation. The initial sharp peak, representing the dye concentration, decreases steadily as ZnO or doped ZnO nanoparticles facilitate the breakdown of rhodamine B into smaller, less complex molecules. The efficiency of degradation depends on the photocatalyst's properties, such as surface area, band gap, and doping. Doping with elements like nitrogen or sulfur enhances visible light absorption and charge separation, increasing degradation efficiency. A complete disappearance of the peak after a specific time indicates the mineralization of rhodamine B into harmless by products like CO_2 and H_2O, confirming the effectiveness of the photocatalyst. Figure 10A–D illustrate the photocatalytic performance of ZnO and P2-ZnO materials for RhB degradation. Figure 10A compares dye removal efficiencies, showing P2-ZnO film (88%) significantly outperforms ZnO powder (25%). Figure 10B highlights time-dependent degradation, where P2-ZnO film achieves ~99% removal in 180 min. Figure 10C presents reaction rate constants, with P2-ZnO film (0.021 min^{-1}) being five times faster than ZnO powder (0.004 min^{-1}). Figure 10D displays UV-Vis spectra, demonstrating a gradual decrease in RhB absorption over irradiation time, confirming the breakdown of dye molecules. These results highlight the enhanced photosensitizing and catalytic efficiency of P2-ZnO films.

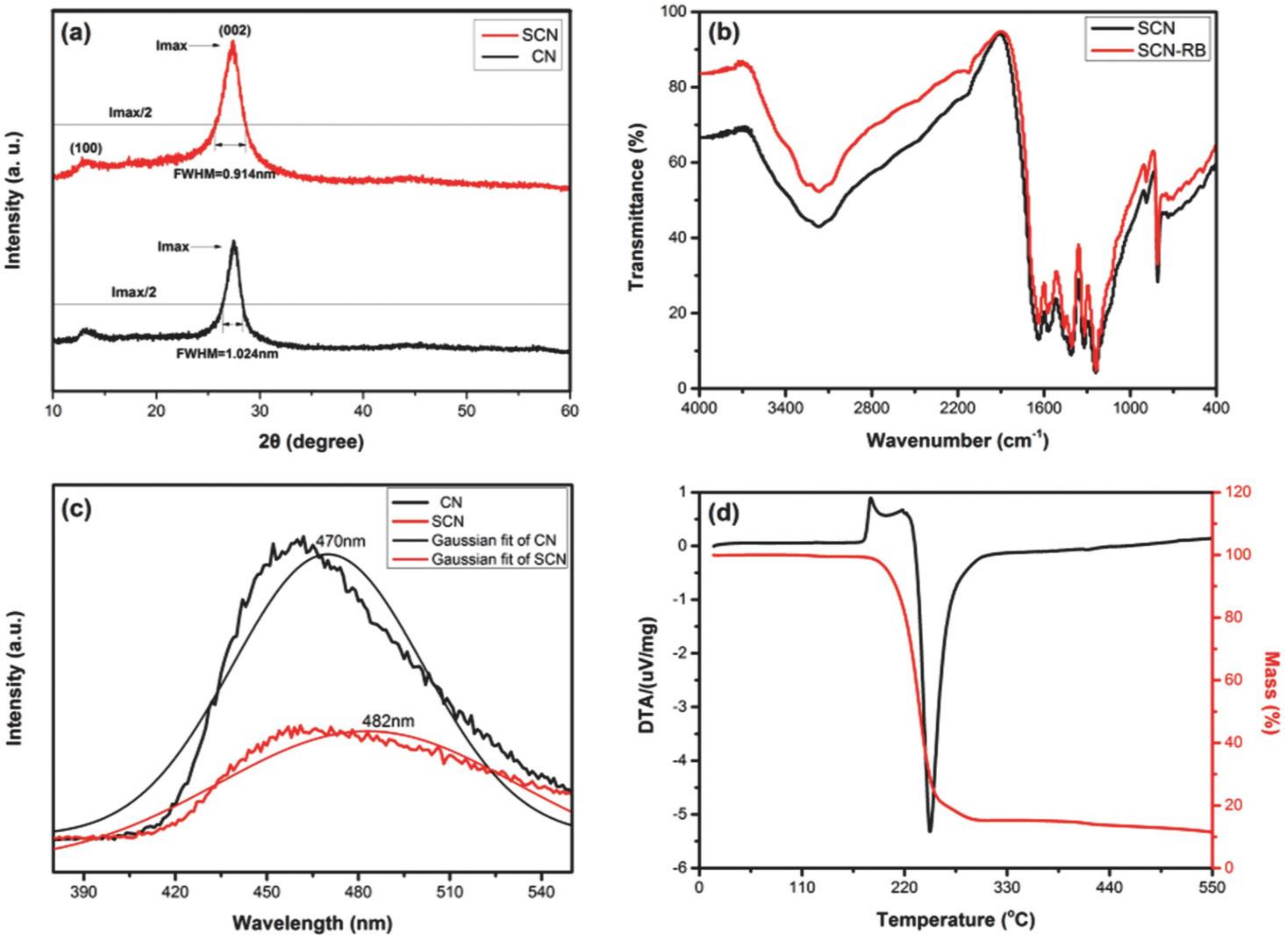

Figure 9. (**a**) XRD of doped and undoped ZnO, (**b**) FTIR, (**c**) Photoluminecence spectra of the respective material, (**d**) TGA/DTA curve [75].

Figure 11 shows a reduction in absorbance at the characteristic wavelength (approximately 664 nm) during the photocatalytic reaction for methylene blue dye. The graph reflects the dye's breakdown into simpler compounds under visible light, catalyzed by ZnO or doped ZnO nanoparticles. The degradation is marked by a gradual decline in the intensity of the absorption peak, showcasing the removal of methylene blue from the solution. Enhanced photocatalysts, especially those doped with elements such as vanadium or sulfur, increase the dye degradation rate by boosting light absorption and suppressing charge recombination. The graph eventually flattens, indicating complete degradation, with the dye converted into non-toxic byproducts.

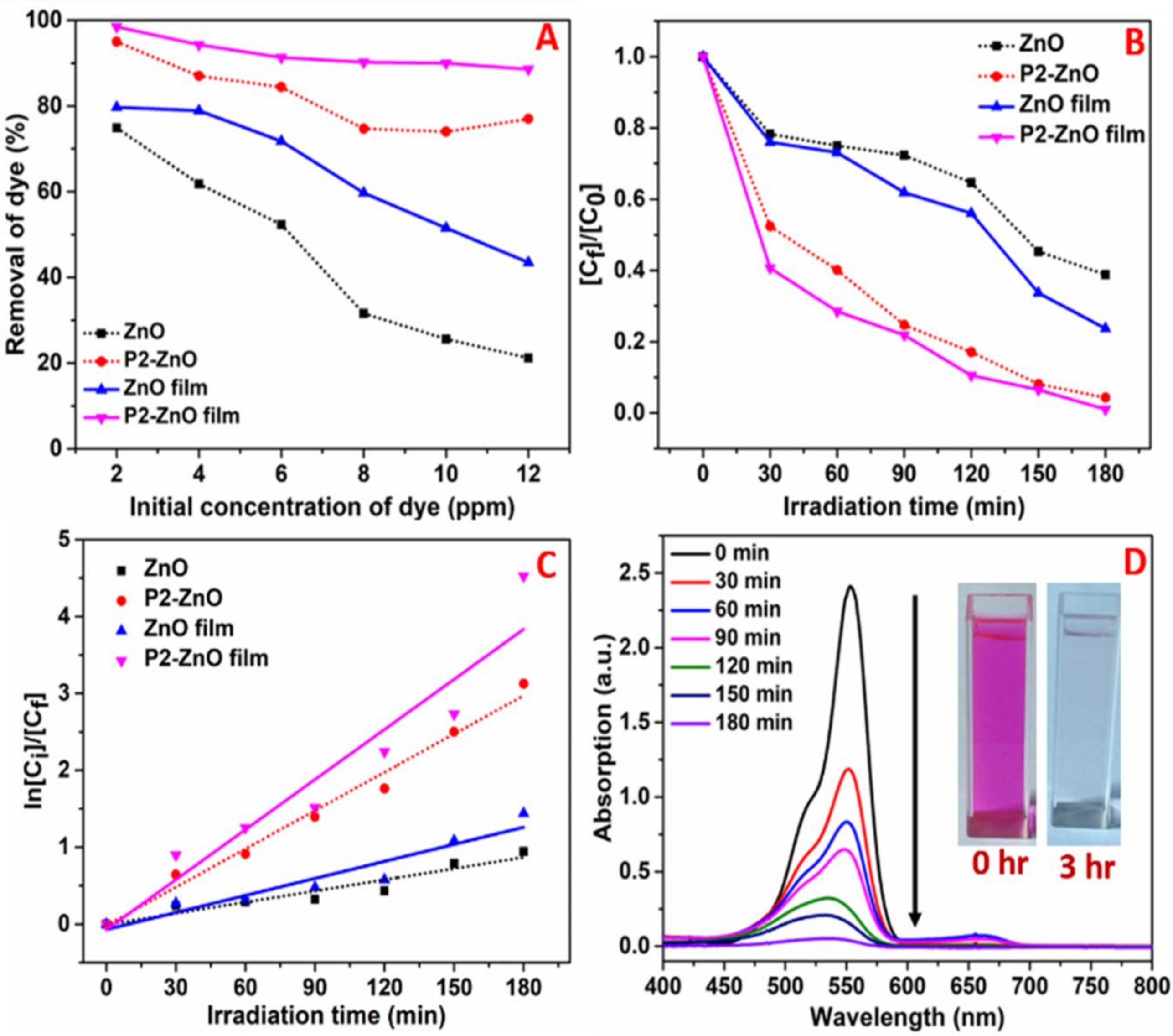

Figure 10. Photocatalytic degradation of Rhodamine B (RhB) using ZnO, P2-ZnO composite, ZnO film, and P2-ZnO film: (**A**) Effect of initial concentration, (**B**) Effect of irradiation time, (**C**) Kinetic study, and (**D**) UV-Vis spectra after irradiation with P2-ZnO film (inset: dye solution before and after 3 h of irradiation) [76].

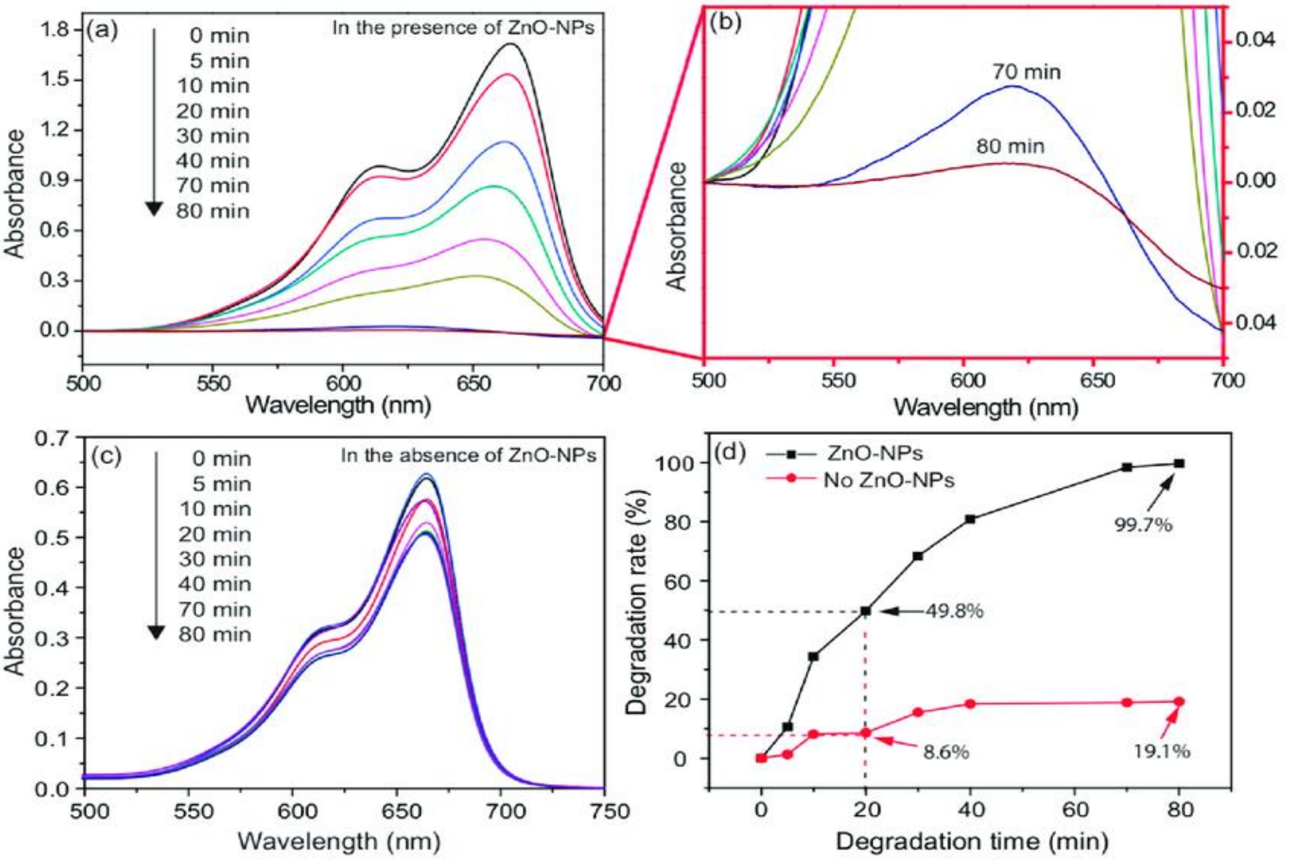

Figure 11. UV-Vis spectra of photocatalytic degradation of methylene blue (MB) dye consuming ZnO composites. (**a**) Dye in the presence of ZnO composites, (**b**) magnified view of panel (**a**,**c**) dye in the absence of ZnO, (**d**) breakdown rate of dye [77].

Kinetic Studies: Degradation kinetics are analyzed to determine the reaction rate constants, providing quantitative measures of photocatalytic efficiency [78].

Reactive Oxygen Species (ROS) Detection:

Chemical Probes: The generation of ROS, such as hydroxyl radicals and superoxide anions, is detected using chemical probes like terephthalic acid and nitroblue tetrazolium, respectively. These probes react with ROS to form fluorescent or color products, which are quantified to assess ROS production.

Stability and Reusability Tests:

Cyclic Testing: Several rounds of pollutant degradation are performed to evaluate the endurance of ZnO photocatalysts, and any performance reduction is measured. This assesses the material's stability and potential for practical applications [78].

4.5. Comparative Analysis with Other Photocatalysts Like TiO$_2$

Zinc oxide (ZnO) and titanium dioxide (TiO$_2$) are widely studied semiconductors in photocatalysis, each possessing unique properties that influence their performance.

Band Gap and Light Absorption:

TiO$_2$ has a band gap of approximately 3.2 eV, limiting its absorption primarily to the ultraviolet (UV) section. In contrast, ZnO exhibits a similar band gap (~3.37 eV) but has been reported to absorb a bigger portion of UV radiation, with a corresponding threshold of 425 nm [79]. This characteristic allows ZnO to utilize a broader spectrum of UV light, potentially enhancing its photocatalytic efficiency under UV irradiation.

Photocatalytic Efficiency:

Both ZnO and TiO_2 are effective in degrading organic pollutants. However, ZnO has been described to have advanced photocatalytic efficacy compared to TiO_2 [79]. This superior performance is attributed to ZnO's ability to engage over a larger section of UV fallout and its higher quantum efficiency.

Charge Carrier Dynamics:

A significant challenge in photocatalysis is the recombination of photogenerated electron–hole pairs, which reduces efficiency. Studies have shown that ZnO experiences a higher recombination rate than TiO_2, leading to a decline in its photocatalytic activity over time [80]. To mitigate this, strategies such as doping and the formation of heterostructures have been engaged to enhance charge separation and extend the lifespan of charge transporters in both materials.

Structural and Morphological Considerations:

The morphology of photocatalysts significantly influences their activity. TiO_2 is commonly synthesized in forms like nanoparticles and nanotubes, while ZnO is often produced as nanorods and nanowires. These nanostructures provide high surface areas, facilitating greater interaction with pollutants and light absorption. For instance, ZnO nanorods have demonstrated enhanced photocatalytic performance due to their elongated structures, which promote efficient charge transport [80].

Synergistic Composites:

Combining ZnO and TiO_2 to form composite photocatalysts has been investigated to control the strengths of both materials. Such composites aim to increase light absorption, improve charge separation, and increase overall photocatalytic efficiency. For example, ZnO/TiO_2 nanocomposites have shown improved photocatalytic activity associated with their counterparts, credited to the synergistic effects between the two semiconductors [79].

Challenges and Future Directions:

Limitations such as photocorrosion, stability, and low quantum efficiency.

Zinc oxide (ZnO) is a widely studied photocatalyst due to its favorable properties, such as a suitable band gap and high electron mobility. However, an array of shortcomings, such as photocorrosion, volatility issues, and low quantum efficiency, prohibit its widespread adoption.

Photocorrosion:

Photocorrosion refers to the degradation of the photocatalyst material itself under illumination, leading to a decline in performance over time. ZnO is particularly susceptible to photocorrosion, especially under prolonged UV exposure. This degradation is primarily due to the oxidation of ZnO, resulting in the dissolution of zinc ions into the solution [66]. To address this issue, surface modifications and the development of ZnO-based composites have been explored to enhance its stability.

Corrosion, Stability, and Synthesis Techniques of ZnO Photocatalysts:

Despite the growing interest in ZnO photocatalysts, significant challenges related to their corrosion resistance and long-term stability in photocatalytic reactions remain underexplored. ZnO materials are susceptible to photocorrosion, especially under prolonged illumination, leading to reduced efficiency and reusability. Stabilization strategies, such as surface modification with inert materials or forming protective layers (e.g., silica or alumina), have shown potential in mitigating these effects [81]. Similarly, doping with elements like Al, Mg, and Fe has been reported to enhance the structural stability of ZnO while improving its photocatalytic activity under visible light [82].

On the synthesis front, traditional methods such as sol-gel, hydrothermal, and precipitation techniques remain widely utilized, but they often result in similar material properties. To overcome this limitation, recent advancements, including microwave-assisted synthesis and flame spray pyrolysis, have been explored to achieve higher surface areas, tailored morphologies, and improved defect engineering [83]. These innovative approaches not only enhance ZnO's photocatalytic performance but also offer scalability for industrial applications. Incorporating such methods alongside strategies to address corrosion and stability challenges is essential for the practical deployment of ZnO photocatalysts in environmental remediation.

Stability Issues:

The structural and chemical stability of ZnO under operational conditions is crucial for its sustained photocatalytic activity. However, ZnO can undergo structural changes and surface modifications during photocatalytic reactions, foremost to a decrease in activity. For instance, the creation of surface defects and the accumulation of reaction intermediates can poison active sites, reducing the competence of the photocatalytic process [66]. Strategies such as doping with other elements and creating heterostructures have been engaged to advance the constancy of ZnO photocatalysts.

Low Quantum Efficiency:

Quantum efficiency is a measure of how effectively absorbed photons are converted into useful chemical reactions. ZnO often exhibits low quantum efficiency as a result of photogenerated electron–hole pairs recombining quickly, which limits the number of charge carriers available for photocatalytic reactions. This recombination process competes with the desired redox reactions, thereby reducing the inclusive efficiency of the photocatalyst [66]. To mitigate this, various approaches have been investigated, including the incorporation of co-catalysts, doping with non-metal foundations, and the formation of Z-scheme heterojunctions to ease efficient charge separation and relocation.

4.6. Potential Improvements for Real-World Applications, Including Stability Enhancements and Practical Scalability

Surface Modification and Doping:

Incorporating dopants into the ZnO lattice can improve its photocatalytic stability. For instance, doping ZnO with elements like nitrogen or sulfur has been shown to enhance its resistance to photocorrosion and extend its operational lifespan [84].

Formation of Heterostructures:

Combining ZnO with other semiconductors, such as titanium dioxide (TiO_2) or graphitic carbon nitride (g-C_3N_4), can create heterostructures that facilitate efficient charge separation. This shrinks the electron–hole pair recombination rate, optimizing photocatalytic stability as well as effectiveness. Such composites can also broaden the light absorption range, making them more effective under solar irradiation [66].

Morphological Control:

Engineering the morphology of ZnO into nanostructures like nanorods, nanowires, or nanosheets upsurges the superficial area available for photocatalytic reactions. This structural optimization not only enhances catalytic performance but also improves the material's mechanical stability, making it more suitable for practical applications [58].

Immobilization Techniques:

Regarding matters connected to the recovery and reuse of ZnO photocatalysts, immobilization on substrates such as glass, ceramics, and polymers has been investigated. This approach prevents the aggregation of nanoparticles and facilitates easy separation from treated media, thereby enhancing the practicality of ZnO in real-world applications [85].

ZnO vs. Other Photocatalysts for Environmental Applications:

ZnO emerges as one of the most promising visible-light-active photocatalysts for environmental applications, outperforming other materials like TiO_2, g-C_3N_4, MOFs, and perovskites in several key aspects. Compared to TiO_2, ZnO exhibits a broader absorption spectrum due to its narrower bandgap, which allows it to absorb a greater portion of visible light, resulting in improved photocatalytic efficiency under natural light conditions [86].

While TiO_2 is a well-established photocatalyst with high stability and reusability, it requires UV light to activate, limiting its practical application. In contrast, ZnO can function effectively under visible light, making it more suitable for energy-efficient processes. [87].

When compared to more complex materials like g-C_3N_4 and MOFs, ZnO offers a distinct advantage in terms of cost and ease of synthesis. While g-C_3N_4 demonstrates impressive stability and photocatalytic performance, its synthesis involves more complex and energy-intensive processes [88]. MOFs, though highly efficient and versatile, are expensive and require multi-step synthesis procedures that hinder their large-scale application [89]. Perovskites, on the other hand, exhibit high efficiency and excellent stability but still face challenges in terms of long-term stability and potential toxicity [90].

ZnO also benefits from simple, scalable synthesis methods, such as sol-gel and hydrothermal processes, which are cost effective and environmentally friendly [91]. This contrasts with the more elaborate synthesis techniques required for g-C_3N_4 and MOFs. Additionally, while ZnO does face challenges with photocorrosion, recent advancements in doping and surface modifications have significantly enhanced its stability and reusability, allowing for 5–6 cycles of efficient pollutant degradation [92]. In summary, ZnO not only offers superior performance in terms of visible light activation and pollutant degradation efficiency but also maintains a competitive edge in cost, ease of synthesis, and stability compared to other photocatalysts. A summary of the above discussion is summarized in Table 4.

Table 4. Comparison of zinc oxide with other catalysts.

Catalysts	Removal Efficiency (%)	Working Conditions	Stability & Reuse	Cost	Ease of Synthesis
ZnO	85–95% (dyes, pollutants)	Visible light, pH 6–9, pollutant-specific	Moderate to High (5–6 cycles with doping)	Low	Very simple (hydrothermal, sol-gel)
TiO_2	75–90% (UV light)	UV light, acidic to neutral pH	High (5+ cycles)	Low	Simple and scalable
g-C_3N_4	90–97% (organic pollutants)	Visible light, pH 6–10	High (6+ cycles)	Moderate	Moderate (thermal polymerization)
MOFs	85–95% (dyes, heavy metals)	Visible light, pollutant-specific	High (7+ cycles)	High	Complex, costly (multi-step synthesis)
Perovskites	90–98% (broad pollutants)	Visible light, wide pH range	High (5–6 cycles)	Moderate to High	Moderate (solution combustion or sol-gel)

Limitations of ZnO Photocatalysts:

Despite the promising potential of ZnO as a photocatalyst, several limitations hinder its widespread practical application. One of the primary challenges is photocorrosion, where ZnO undergoes structural degradation under prolonged exposure to light, reducing its photocatalytic efficiency over time [93]. Additionally, low quantum efficiency under visible light remains a concern, as ZnO predominantly absorbs in the UV range, limiting its effectiveness under natural sunlight [94]. Stability issues, particularly under harsh environmental conditions, can further reduce the longevity and performance of ZnO-based catalysts.

Moreover, ZnO's poor charge separation efficiency often leads to the recombination of electron–hole pairs, reducing its catalytic activity. While doping and morphological modifications have shown promise in enhancing its performance, they also introduce challenges related to reproducibility and scalability. Furthermore, large-scale synthesis and immobilization techniques still require optimization to ensure cost-effectiveness and practical feasibility. Addressing these limitations through ongoing research will be key to unlocking ZnO's full potential in environmental and energy applications.

5. Conclusions

Zinc oxide (ZnO) has emerged as a versatile and promising photocatalyst, offering significant potential in environmental remediation and energy applications due to its favorable band gap, high electron mobility, and exceptional photocatalytic properties. Its wide-ranging applicability in the degradation of organic pollutants, disinfection of water, and breakdown of airborne volatile organic compounds (VOCs) underscores its environmental significance. Moreover, ZnO's potential for hydrogen generation through water splitting highlights its promise as a clean energy solution. Despite these advantages, challenges such as photocorrosion, stability concerns, and low quantum efficiency continue to limit its practical use in real-world applications. To address these limitations, various strategies have been explored, including non-metal and metal doping, heterostructure formation, and morphological control. These approaches aim to enhance ZnO's light absorption, charge separation efficiency, and overall catalytic performance. Additionally, coupling ZnO with other semiconductors, such as titanium dioxide (TiO_2), and employing immobilization techniques have proven effective in overcoming scalability and operational challenges, enabling its integration into large-scale processes. Advancements in synthesis methods, including the development of novel nanostructures and surface modifications, are focused on improving the stability, efficiency, and practical scalability of ZnO-based photocatalysts. These innovations not only enhance the material's performance but also extend its lifespan, making it more viable for commercial and industrial applications. As a result, ZnO is emerging as a frontrunner in the field of sustainable photocatalysis, with potential applications spanning from environmental cleanup to clean energy production. However, to fully unlock the capabilities of ZnO and realize its wide-scale implementation, continued innovation and interdisciplinary efforts are essential. Researchers must focus on optimizing the material's properties, developing cost-effective production methods, and addressing real-world challenges such as stability and long-term performance. With ongoing advancements and concerted efforts across various fields, ZnO has the potential to play a pivotal role in driving the transition towards more sustainable technologies, offering solutions to some of the most pressing environmental and energy challenges of our time.

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