

Review

Photocatalytic Degradation of Microplastics in Aquatic Environments: Materials, Mechanisms, Practical Challenges, and Future Perspectives

Yelriza Yeszhan ^{1,*} , Kalampyr Bexeitova ¹ , Samgat Yermekbayev ¹, Zhexenbek Toktarbay ¹ , Jechan Lee ² , Ronny Berndtsson ³  and Seitkhan Azat ^{1,*} 

- ¹ Laboratory of Engineering Profile, Satbayev University, Satbayev Str. 22, Almaty 050000, Kazakhstan; kalampyr.bexeitovas@gmail.com (K.B.); sky.statute@gmail.com (S.Y.); zhexenbek.toktarbay@nu.edu.kz (Z.T.)
- ² Department of Global Smart City & School of Civil, Architectural Engineering, and Landscape Architecture, Sungkyunkwan University, Suwon 16419, Republic of Korea; jechanlee@skku.edu
- ³ Division of Water Resources Engineering & Centre for Advanced Middle Eastern Studies, Lund University, P.O. Box 118, SE-22100 Lund, Sweden; ronny.berndtsson@tvrl.lth.se
- * Correspondence: yeszhan.y@stud.satbayev.university (Y.Y.); s.azat@satbayev.university (S.A.)

Abstract

Due to its persistence and potential negative effects on ecosystems and human health, microplastic pollution in aquatic environments has become a major worldwide concern. Photocatalytic degradation is a sustainable manner to degrade microplastics to non-toxic by-products. In this review, comprehensive discussion focuses on the synergistic effects of various photocatalytic materials including TiO₂, ZnO, WO₃, graphene oxide, and metal–organic frameworks for producing heterojunctions and involving multidimensional nanostructures. Such mechanisms can include the generation of reactive oxygen species and polymer chain scission, which can lead to microplastic breakdown and mineralization. The advancements of material modifications in the (nano)structure of photocatalysts, doping, and heterojunction formation methods to promote UV and visible light-driven photocatalytic activity is discussed in this paper. Reactor designs, operational parameters, and scalability for practical applications are also reviewed. Photocatalytic systems have shown a lot of development but are hampered by shortcomings which include a lack of complete mineralization and production of intermediary secondary products; variability in performance due to the fluctuation in the intensity of solar light, limited UV light, and environmental conditions such as weather and the diurnal cycle. Future research involving multifunctional, environmentally benign photocatalytic techniques—e.g., doped composites or composite-based catalysts that involve adsorption, photocatalysis, and magnetic retrieval—are proposed to focus on the mechanism of utilizing light effectively and the environmental safety, which are necessary for successful operational and industrial-scale remediation.

Keywords: photocatalysis; environmental remediation; plastic pollution; metal–organic frameworks; advanced oxidation processes



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1. Introduction

Microplastics (MPs), defined as tiny plastic particles with sizes ranging from less than 5 mm to as small as 50 µm, have become a significant environmental concern in the last few decades due to their ubiquitous occurrence in all water bodies [1]. For comparison with work dealing with the photocatalytic degradation phenomena, we adhere to this

50 μm bound in this review, as particle sizes above this limit are more often analyzed and reported. These particles are known to adsorb and transport pollutants, posing risks to both ecosystems and human health [2]. The sources of MPs in water systems include wastewater discharge, plastic litter fragmentation, and atmospheric deposition [3]. Wastewater treatment plants have been identified as significant contributors to microplastic pollution, which deliver the particles into rivers, estuaries, and coastal areas [4] ultimately reaching our food chains [5,6].

Of the technologies reported to be applied to MP pollution, four conventional strategies—chemical degradation, advanced oxidation processes (AOPs), electrochemical methods, and ozonation—have been used extensively in laboratory and pilot-scale studies. Chemical oxidants (e.g., Fenton's reagent, persulfate) easily break down multiple-unit polymers but can potentially produce more toxic secondary byproducts and need repetitive reagents supplemented during treatment [7]. AOPs employ UV, H_2O_2 or O_3 to generate strong radicals; however, they suffer from high chemical consumption and energy use, and cause by-product formation [8]. Electrochemical technologies are able to mineralize MPs without additional chemicals, but relatively high-power consumption and fouling of electrodes restrict long-term operation [7]. Ozone swiftly targets unsaturated chemical bonds, but it has limited selectivity, a short lifespan, and requires costly on-site production [7].

Another approach that has been studied recently is the photocatalytic degradation, which is based on light-activated semiconductor materials, e.g., TiO_2 or ZnO , leading to the generation of the ROS in situ and causing the stepwise oxidation of MPs towards the formation of CO_2 and H_2O under relatively mild conditions [9,10]. Only irradiance is required in the case of sunlight, making photocatalysis have a smaller energy and carbon footprint than electrochemical or ozone technologies. Moreover, the catalyst films, powders or newly self-propelled micromotors can be collected for recycled use, thus mitigating the secondary-pollution problems of homogeneous oxidants. Recent works have reported >90% of mineralization of polyethylene and polystyrene at solid–solid interfaces as well as efficient collection–degradation on TiO_2 micromotors [11]. Collectively, these properties place photocatalysis as a practical and environmentally friendly option, which justifies focus of the review.

The mechanisms underlying photocatalytic degradation involve not only the generation of reactive oxygen species (ROS) but also the structural properties of the MPs themselves. It has been well recognized in the literature that polyolefins, such as polyethylene and polypropylene, are fragmentation resistant because they have a stable chemical structure. Yet, its comparably high oxygen permeability leads to a faster diffusion of the ROS produced by the photocatalyst into the polymer matrix, facilitating oxidative chain scission once initiated [12]. Such fragmentation is critical since MPs possess greater solubility in solvents, leading to an increased potential for degradation [12]. Additionally, the incorporation of nanomaterials within photocatalytic systems has demonstrated enhanced degradation efficiencies due to their large surface area and tunable bandgap, optimizing light absorption and ROS generation [13].

Apart from traditional photocatalytic methodologies, novel approaches like self-propelled photocatalytic micromotor use have also been suggested. These micromotors, propelled by different mechanisms including catalytic (e.g., H_2O_2 -powered), photochemical, photothermal, or magnetic, can thus actively target and operate on microplastics in aqueous environments. Their mobility provides microplastics with increased chances to collide with the suspended pollutants, breaks the mass transfer limitations typical of static systems and causes localized ROS generation at the microplastic surface [14]. Magnetic

micromotors, specifically, enable directionality and post-processing retrieval, enhancing efficiency and sustainability. These systems are further described in detail in Section 2.4.

This strategy not only addresses the challenge of effectively contacting MPs with catalysts but also introduces a scalable solution for environmental remediation [15]. While photocatalytic degradation is undeniably a promising area of consideration, there are challenges to overcome, including ensuring complete mineralization and managing the possible formation of secondary MPs and hazardous by-products from the degradation process [16]. Therefore, ongoing research is essential to refine these methods and develop comprehensive strategies that integrate photocatalytic degradation with other advanced oxidation processes (AOPs) to enhance overall efficiency and safety in MP remediation [17].

Photocatalytic degradation represents a promising avenue, leveraging light-activated catalysts to degrade MPs into less harmful compounds. For example, Nabi et al. demonstrated that TiO_2 nanoparticles could achieve complete mineralization of MPs when applied in a solid phase, significantly outperforming liquid-phase applications. This improvement is reasoned out to be effective in interaction of solid–solid interface, where the photocatalyst is directly attached to the polymer surface. These structures enhance adsorption and decrease mass-transfer resistance of short-lived ROS to the interface and favor the charge separation over the interface, which is advantageous for retarding recombination of e^-/h^+ , so as to improve the photocatalytic efficiency [18]. Additionally, photocatalytic micromotors made from TiO_2 , which not only remove MPs from water, but also facilitate their degradation. These micromotors can be controlled magnetically, allowing them to effectively “shovel” MPs, thereby increasing the contact area between the photocatalyst and the pollutants [14]. However, several challenges must be overcome, including complete mineralization and potential formation of toxic by-products. Continuous study of photocatalytic materials and other oxidation mechanisms is needed for performing integrated and green alternatives for MP residual remediation.

This review is crucial due to the increasing global concern over MP pollution in water and the shortcomings of current remediation approaches. Induced by this phenomenon, there is noticeable growing academic interest in this area, as indicated by the number of published papers on studies of degradation of microplastics with photocatalysts over the last five years (Figure 1). This indicates the urgent necessity to summarize existing evidence and test potentially useful photocatalytic solutions to address microplastic pollution in the aquatic system.

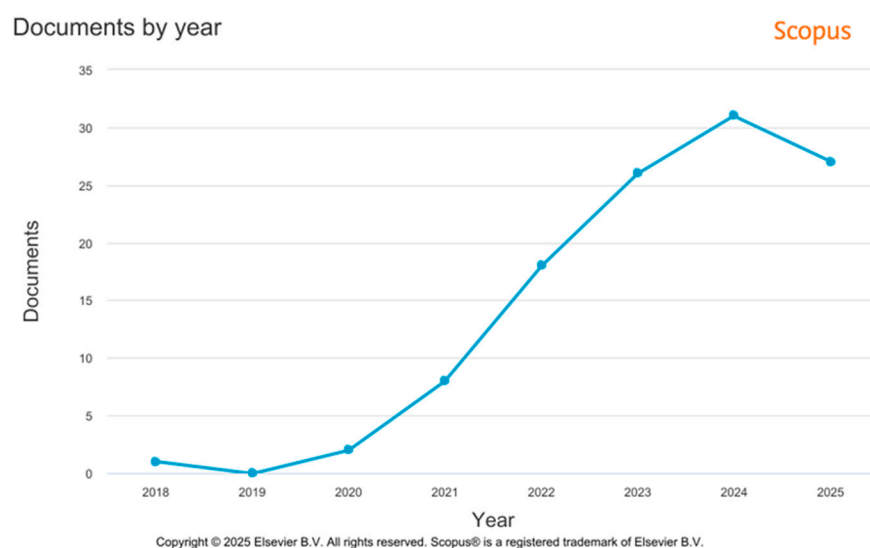


Figure 1. Number of Publications on Photocatalytic Degradation of Microplastics (2020–2025).

Unlike previous reviews that focused on photocatalysis for pollutant removal in general, this work specifically addresses the challenges and recent advancements in photocatalytic materials for degrading MPs. It highlights key issues such as achieving complete mineralization and preventing the formation of harmful by-products, critically evaluating innovative strategies developed to overcome these obstacles. Additionally, this review stands out by covering a diverse range of photocatalytic materials, including TiO₂, ZnO, and various composites, assessing their performance under different environmental conditions. A strong emphasis is placed on optimizing photocatalyst properties—such as structural design, reactive oxygen species (ROS) generation, and surface area—to improve MP degradation efficiency. Moreover, by discussing alternative reactor configurations, this review explores the scalability and real-world applications of photocatalytic techniques, offering valuable insights for advancing sustainable MP removal strategies.

2. Performance of Photocatalysts for the Degradation of MPs

Numerous materials have been studied for photocatalytic degradation of MPs, such as TiO₂, ZnO, graphene oxide (GO), WO₃, and CdS, which showed potential in this field. Additionally, advances in nanocomposites, hybrid materials, and metal–organic frameworks (MOFs) have further improved the photocatalytic performance in microplastic degradation.

Table 1 provides a summary of TiO₂, ZnO, GO, WO₃, CdS, and MOFs, including bandgap energy, light absorption range, main physico-chemical properties, synthesis or modification methods, and (limited) photocatalytic efficiencies and limitations, focusing on microplastic degradation. The photocatalytic behaviors of these photocatalysts will be detailed in the following subsections.

Table 1. Photocatalytic performance of various materials.

Material	Bandgap Energy (eV)	Light Absorption	Physicochemical Properties	Synthesis/ Modification Method	Photocatalytic Efficiency and Limitations
TiO ₂	≈3.0–3.2 (rutile and anatase)	Primarily UV	High stability, electron-hole re-combination issues	Nanostructuring (nanotubes, nanowires), doping, composites (e.g., with activated carbon)	Efficient under ultraviolet light, with minimal visible light exposure and a high rate of electron-to-proton recombination. The degradation rates reported for polyethylene and polystyrene microplastics under optimal laboratory conditions range from 70 to 99%.
ZnO	≈3.2	Primarily UV	High surface area, adaptable morphology	Nanostructuring (nanorods, nanoflowers), doping (e.g., Ag, In), composites with reduced GO	Similarly to TiO ₂ , it is primarily active under ultraviolet light due to its large energy gap (~3.3 eV). However, it performs poorly under natural sunlight and is susceptible to the recombination of electrons and protons. The activity of this material is dependent on its morphology.

Table 1. Cont.

Material	Bandgap Energy (eV)	Light Absorption	Physicochemical Properties	Synthesis/Modification Method	Photocatalytic Efficiency and Limitations
GO	2.4–4.3 eV	UV and Visible	High surface area, excellent electron mobility	Used as a composite with semiconductors like TiO ₂ to enhance charge separation	Improves the efficiency of charge transfer and increases the surface area in composite materials. The cost and complexity of synthesis are primarily linked to the production of pure GO and GO-based nanocomposites through chemical exfoliation or the Hummers method.
WO ₃	≈2.7	Visible	Moderately stable, good ROS production	Doping, composite formation	Limited efficiency under sunlight without modifications.
CdS	≈2.4	Visible	High ROS production, toxicity concerns	Used in composites to stabilize and enhance degradation	Effective, but limited by toxicity and environmental safety concerns.
MOFs	Varied depending on metal nodes, linkers, structure, defects, and modifications	UV and Visible	Porous structure, tunable, high adsorption	Hybrid with metals, organic ligands	High charge separation, scalable; complex synthesis.

The utilization of photocatalytic based (PT) systems for MP degradation in aquatic environments raises urgent questions in terms of environmental safety associated with the presence of residual nanomaterials and the toxicity of intermediate degradation by-products. Though the goal of photocatalysis is the complete mineralization of MPs into harmless components, such as carbon dioxide and water, this is rarely achieved in practice [16]. Suboptimal light or catalysis can result in incomplete degradation, leading to the formation of potentially reactive, persistent, or bioaccumulative intermediates; and uncertainties in leaching, aggregation, and long-term fate of the nanomaterials (e.g., TiO₂, ZnO, GO) have raised the concern that full environmental risk assessments should be undertaken before the methods find field scale application [16].

Incomplete photocatalytic degradation could generate low molecular weight fragments, oxidized polymers, or chemically converted by-products which retain or increase the toxicity of original MP pollutants. Indeed, MPs can also release various substances or form new compounds during oxidative fragmentation; some examples are the leaching of additives (i.e., plasticizers, flame retardants, heavy metals) or the formation of chemicals (e.g., aldehydes, alcohols, peroxides) [19]. These byproducts are known to cause adverse effects in aquatic organisms such as oxidative damage, membrane disturbance, and endocrine interference. Even if mineralization is almost completed, the transformation products in trace concentrations can continue to interact with other pollutants in aquatic environments in a synergistic manner and this can aggravate their environmental impact. Therefore, the ideal MP remediation should not only have high decomposition efficiency but also ensure that its intermediate and final products do not result in secondary ecological risk [20].

As degradation byproducts, the reactivity to the environment concerning the nanomaterials employed as photocatalysts, the behavior as well as the stability play a significant role in terms of environmental compatibility. TiO₂ is commonly used owing to its photostability, and regulation agencies consider it non-toxic under sunlight exposure. However, the

long-term UV irradiation may lead to surface photocorrosion, particularly for doped or composite types, accompanied by the release of both titania ions and co-catalyst species. Leaching of these substances into the aquatic environment might change microbial communities or nutrient cycles [21]. Likewise, ZnO compounds are highly photocatalytic, and also dissolve under acidic or salt conditions, which can result in the production of free Zn^{2+} ions—a known toxin in water at high levels. Agglomerate ZnO nanoparticles also have a significantly smaller specific surface area and less photocatalytic activity, complicating more the environmental behavior of nanomaterials [22].

Graphene oxide has been extensively used in composite photocatalysts due to its large specific surface area and high electron mobility, but it may cause some environmental persistence problems. GO can sustain colloidal stability under water for a long time, and it is found to adsorb organic pollutants and metal ions, and thus, can be secondary vectors for the transfer of contaminants. Although subject to continuing investigation, it has been found that GO might cause cellular stress to aquatic life, especially under high concentration and/or attached with reactive groups. The long-term effects of low-dose or environmentally relevant chronic exposure to GO is poorly understood as regards GO and to similar carbonaceous nanomaterials and are still in need of further toxicological and ecotoxicological investigation [23].

Beyond individual material considerations, the interplay of nanomaterials and MPs during photocatalysis may create even hybrid residues—multifaceted accumulations of partly degraded plastics, captured nanoparticles, and surface-attached pollutants [24]. These hybrid by-products might be even more permanent (or more bioavailable) than the MPs themselves and even evade traditional filtration processes employed for water treatments. Upon entering the bodies of aquatic species, they could be accrued through the food chain and have the potential for sublethal effects, including growth arrest, spermatogenic impair, and immune suppression. In particular, the microplastics can serve as vectors for nanomaterials, and conversely, enhance their environmental effects [25].

Given these challenges, the future advancement of photocatalytic systems for the treatment of microplastics must prioritize both effectiveness and environmental friendliness. Approaches could involve biodegradability in the case of photocatalysts, immobilization of nanomaterials in an inert matrix to prevent nanoparticles leaching, or magnetic recovery systems for end-of-treatment collection. Importantly, photocatalytic activity studies need to be accompanied by a thorough toxicity profiling—including assays on aquatic toxicity, biodegradability, and bioaccumulation potential—to prevent the treatment from being worse than the disease. In this area, regulatory criteria and strategy of the nanomaterials used for water treatment are still under development, and interdisciplinary cooperation is essential in addressing the gap between materials science and environmental chemistry/ecotoxicology.

Among the popularly employed photocatalyst material, TiO_2 can be counted as one of the safest due to its inertness, photostability, and regulatory approval for different environmental applications [26]. In contrast, CdS-based products, which can be very efficient, are recognized to release toxic cadmium ions into the environment [27]. Although ZnO is a common material as an antimicrobial agent, it can be dissolved under acidic or saline conditions, and its released Zn^{2+} ions are toxic at high concentrations [28]. Graphene oxide (GO) has lower acute toxicity but acts as a vector for co-contaminants because of its strong adsorption ability [29]. Nanoparticles such as MOFs (especially those with iron or zinc with biocompatible linker) have been found to have promising environmental safety profile in recent studies, although long-term ecotoxicological data is still quite limited [30]. Therefore, when considering a scalable solution for MP remediation, the choice of materials

is not only a question of efficiency but also on how toxic or persistent a byproduct may be in the environment.

Beyond the toxic side effects of degradation products, the efficiency of microplastic removal is more complex when MPs are treated in a more realistic wastewater matrix, such as when they are present alongside a variety of other pollutants.

The existence of microplastics (MPs) in wastewater is widely accepted as a severe environmental problem, not only owing to their endurance and prevalence, but also because of their frequent coexistence with a plethora of organic and inorganic co-pollutants [31]. In actual wastewater scenarios, MPs are seldom in an unbound state, and they are mostly present suspended together with surfactants, pharmaceuticals, heavy metals, solvents, and nutrients in intricate mixtures of contaminants. Such coexistence gives rise to important questions on the efficiency of photocatalytic and biological degradation and on the interactions—synergistic or antagonistic—that can occur between different types of contaminants during the treatment. These interactions are important to understand for developing feasible and scalable methods for MP removal in real-life wastewater treatment plants.

Numerous studies show that the degradation behavior of MPs in real wastewater is influenced by chemical as well as biological properties. Surface-active organics such as surfactants or simple hydrocarbons can be co-substrates for microbial communities, possibly stimulating biodegradation through the stimulation of microbial metabolism or through modification of surface relationships between microbes and plastic particles. But this positive effect is very content sensitive. For example, heavy metals, ranging from cadmium, lead, and mercury, can have a severe cytotoxic impact on microbial consortia, resulting in the inhibition of biodegradation as well as blocking of photocatalytic processes by adsorbing to catalysts [32]. In such circumstances, the MP removal efficiency may be considerably lower than lab-controlled conditions. Competing pollutants can also absorb ROS produced during photocatalysis, reducing oxidative attack on MP surfaces. In addition, partial degradation of MPs in the co-presence of other pollutants can facilitate the generation of more persistent or more toxic by-products, creating further risk for the environment [33].

Realistic wastewater-based studies including experiments with spiked effluents and with samples generated from membrane bioreactor (MBR) systems contribute to an increased understanding of these interactions. For example, Kwon et al. and Liu et al. assessed the impact of MP addition on activated sludge systems and observed significant variation in degradation efficiencies depending on polymer type and co-pollutant content. Polyethylene and polyvinyl chloride particles only marginally inhibited bacterial activity under some conditions, but removal performance was extremely dependent on operation situation and background contaminants [34,35]. Similarly, Talvitie et al. (2017) showed that even though tertiary wastewater treatment such as filtration and sedimentation could potentially remove more than 99% of MPs from water under optimal conditions, the removal efficiency decreases substantially in complex matrices with high organic matter content, surfactants, or competing particles [36]. Dynamic interplay between MPs and co-pollutants can affect not only degradation rates but also physicochemical transformations of MPs during the treatment process.

Wastewater matrix complexity is also an important factor affecting MPs aggregation, sorption, and photoreactivity. Components like electrolytes, colloids, humic substances, etc., may influence the electric charge on MP's surface or their potential to agglomerate or bond onto catalysts or reactor surfaces. The hydrophobicity of MPs could be affected by surfactants and dissolved organic matter to become more dispersed or more fouled on the reactor's components. In membrane processes, these phenomena could inhibit filtration efficiency and enhance microplastics breakthrough in effluents [35]. Furthermore, the

synergy of MPs with co-contaminants can generate hybrid particles, not easily degradable or removed, that can play a role of transport vectors for the PPs. The simultaneous effects further justify the requirement for degradation strategies that are resistant to real scenario conditions, considering wastewater composition of multicomponent nature [37].

In general, the degradation of microplastics in wastewater systems cannot be understood in isolation from co-occurring contaminants. Some pollutants are capable of supporting degradation by supplying microbial or catalytic co-factors, while others hinder treatment operation by toxicity, ROS scavenging or structural obstacles. Increasing evidence from spiked wastewater studies, from effluent trials with MBRs, and from integrated treatment studies has underlined the role of matrix complexity in influencing the degradation of GPs. Adaptation of photocatalytic and biological treatment technologies towards the complex system—based on catalyst optimization, pre-treatment, or hybridization will be key to obtain practical and sustainable MP elimination. As the research continues, interdisciplinary research linking material science, wastewater engineering, and environmental toxicology will be crucial in developing real-life solutions for the remediation of microplastics.

2.1. Titanium Dioxide

TiO₂ is a well-established photocatalyst that has garnered extensive attention for its capacity to degrade MPs. It is a semiconductor material with a wide bandgap, approximately 3.0 electron volts (eV) in the case of rutile and approximately 3.2 eV for anatase, which predominantly absorbs ultraviolet (UV) radiation [38]. The photocatalytic activity of TiO₂ is attributed to its capacity to generate electron-hole pairs upon light absorption. These electron-hole pairs subsequently interact with water and oxygen, resulting in the formation of reactive oxygen species, including hydroxyl radicals (•OH) [39]. These ROS are highly active and play a crucial part in the breakdown of organic contaminants, including MPs, by fragmenting intricate polymeric structures into simpler, harmless components [40].

The doping of TiO₂ with diverse elements can substantially augment its photocatalytic performance, particularly in the presence of visible light. For example, sulfur doping into the TiO₂, for instance, reduces band gap energy by the creation of impurity state—mainly from sp³ states—within the band energy. These intermediate levels of delocalization in energy are conducive to the visible light absorption and more long-wavelength-driven photogeneration of the electron-hole system, respectively, which is beneficial to the photocatalysis [41]. This modification creates intermediate energy levels within the bandgap, facilitating the generation of electron-hole pairs under visible light irradiation.

Creating composites of TiO₂ with other materials can further enhance its photocatalytic efficiency. For instance, the incorporation of activated carbon or other semiconductors can improve charge separation and reduce electron-hole recombination [42]. Such composites have demonstrated enhanced photocatalytic activity for the degradation of organic pollutants, including dyes and MPs [43]. The combination with heterojunctions such as silver oxide or zinc oxide would further extend the light absorption spectrum and improve charge transfer, thereby enhancing photocatalytic performance [7]. The work of Fadli et al. [44] demonstrated that modifying TiO₂ with silver and reduced GO (rGO) significantly increased its photocatalytic capabilities under UV irradiation, achieving substantial degradation of polyethylene MPs. The study utilized various characterization techniques to confirm the enhanced properties of the modified composites, which were tested over a 4 h period. In this regard, another study synthesized Ag/TiO₂ nanocomposite and evaluated its potential to degrade MPs in water, where both showed that the addition of silver nanoparticles enhanced the photocatalytic degradation performance of MPs [45]. The influence of pH and temperature on the process of HDPE MPs degradation was explored using N-TiO₂

and visible light as catalysts. The degradation process was monitored by measuring mass loss, calculating the carbonyl index, and employing microscopy techniques. Photocatalytic degradation at low temperature (e.g., 0 °C) was found to promote the increase in microplastics surface area induced by embrittlement of the material and associated with fragments which can be further attacked by ROS. Likewise, a low pH (pH 3) promotes the generation of hydroperoxides, promoting the proton-catalyzed transformation of reactive species like ($\text{O}_2^- \bullet$) to more oxidative forms such as H_2O_2 and facilitating degradation processes [46].

The synthesis of TiO_2 in various nanostructured forms, such as nanotubes, nanowires, or nanoflowers, can significantly increase its surface area and improve its photocatalytic activity [47]. Compared with their bulk counterparts, these nanostructures show better light-absorption capacity and more active sites for photocatalytic reaction on the surface, allowing enhanced degradation rates of organic pollutants [47]. For instance, the synthesis of hierarchical TiO_2 nanostructures has been shown to enhance photocatalytic activity significantly. Ochanda et al. investigated the controlled synthesis of TiO_2 hierarchical nanofibers and demonstrated their superior photocatalytic performance in degrading organic pollutants, including dyes, which can be analogous to MPs in terms of degradation mechanisms [48].

TiO_2 nanofilms served as a catalyst for the photolytic disintegration of polyethylene and polystyrene nanoparticles under the influence of ultraviolet radiation. Under optimal laboratory conditions, 98.4% MP's degradation was obtained in 12 h, with near complete mineralization in 36 h. Intermediates comprising carbonyl, hydrocarbon, and hydroxyl groups, with CO_2 as the final product. Although this is evidence of the potential of TiO_2 systems, complete mineralization is poorly achieved in the majority of studies, especially in the presence of environmental or low-intensity light [18]. Pure TiO_2 nanorods have also been successfully employed for the degradation of MPs. For a pH of 3 and an ambient temperature of 0 °C, the weight of MP particulates diminished by 60% after a period of 50 h under irradiation from a 50 W LED lamp [46,49]. The TiO_2 nanoparticle film synthesized in the presence of the surfactant Triton X-100, exhibited complete mineralization (98.4%) of 400 nm PS in 12 h, and the degradation of PS was recorded depending on size. After 36 h, the photodegradation experiment of PE showed a high photodegradation rate with CO_2 as the main final product [18]. In the study of Wang et al., an efficient photocatalyst Ag/TiO_2 was prepared by a photo-assisted deposition method, and the photocatalytic degradation of polyamide66 (PA66) was conducted under UVA irradiation. Under UVA irradiation, the photocatalyst/PA66 mass ratios of 1:1 and 3:1 exhibited effective degradation rates of PA66. Furthermore, the more Ag/TiO_2 was added, the more complete PA66 photocatalytic degradation was, increasing C=O formation and complete oxidation of CH_2 [50].

Even though TiO_2 has many benefits, it still has many limitations that can hinder its photocatalytic activity. TiO_2 absorbs mainly in the UV, which is only a tiny part of the solar spectrum. However, this limitation restricts its efficiency in the presence of natural sunlight [47]. One of the important drawbacks in TiO_2 photocatalysis is that the recombination of photogenerated electron-hole pairs occurs rapidly. This process decreases the number of charge carriers available to perform redox reactions, leading to low overall photocatalytic efficiency [51]. Modification strategies aimed at enhancing charge separation are essential to mitigate this issue.

The performance of different TiO_2 -based materials for microplastic degradation is summarized in Table 2.

Table 2. Performance of TiO₂ for the degradation of MPs.

Material	Reactor Type	Reaction Condition	Degradation Efficiency	Reference
TiO ₂ nanofilms	Batch reactor	UV radiation	After 12 h, the decomposition of 98.4% was observed, and after 36 h, the decomposition was complete for both the polyethylene and polystyrene microspheres.	[18]
TiO ₂ nanorods	Batch reactor	pH of 3 and a temperature of 0 °C, irradiation with a 50 W LED lamp	The mass of microplastic particles decreased by 60%	[46,49]
N-modified TiO ₂	Batch reactor	pH = 3, temperature 0 after 50 h reaction under visible light irradiation	The highest mean weight loss was 71.77% for HDPE	[46]
GO-TiO ₂	Batch reactor	72 W UV lamp with a wavelength of about 350 nm	50.46% after 480 min of degradation	[52]
TiO ₂ nanoparticle films	Batch reactor	Made with Triton X-100; under UV light irradiation	The complete mineralization of 400 nm PS particles within 12 h, achieving a mineralization rate of 98.40%.	[18]
Ag/TiO ₂ composite	Batch reactor	UVA irradiation, mass ratio of photocatalyst to PA66 1:1 and 3:1	significant degradation of PA66	[50]

2.2. Zinc Oxide

Another semiconductor that is being widely studied in terms of photocatalytic activity, especially for the removal of MPs, is zinc oxide (ZnO) (Table 3). ZnO exhibits strong photocatalytic activity due to its ability to generate electron-hole pairs upon exposure to light. When ZnO absorbs photons with energy greater than its bandgap (approximately 3.2 eV), electrons are excited from the valence band to the conduction band, creating electron-hole pairs [53]. The generated holes can oxidize water or hydroxyl ions to produce ROS, such as hydroxyl radicals (OH), which are highly effective in degrading organic pollutants, including MPs [54].

ZnO nanoparticles having a high surface area, would facilitate photocatalytic efficiency by increasing the active sites for the reactions [55]. Improved degradation rates of MPs result from better light absorption and more available active sites for the photocatalytic reactions in such nanostructures [56]. Morphological control, for example, to produce nanorods or nanosheets, may result in the increase in surface area from over ~10 m²/g (bulk) to 50–100 m²/g, or even more, depending on the synthesis conditions [57]. These designed structures improve the absorption of contaminants, the utilization of light, and the production of ROS. For example, ZnO nanorods have demonstrated enhanced photocatalytic activity for the degradation of low-density polyethylene (LDPE) MPs, effectively breaking down the polymer structure [54].

Combining ZnO with other materials can further enhance its photocatalytic properties. For example, it has been demonstrated that preparing ZnO composites with GO-enhanced light absorption and charge separation, resulting in activity under visible light [58]. These composites can degrade organic pollutants and MPs in the presence of electrons, resulting from the synergistic effects of the combined materials [59].

It has been reported that under UV and visible light irradiation, self-doped ZnO is effective in degrading different types of MPs. According to studies, ROS can be generated by ZnO and interact with the polymer chains of MPs, resulting in the fragmentation of polymers into smaller oligomers and finally the mineralization of the MPs into innocuous products [60]. Additionally, the properties of ZnO and the incorporation of co-catalysts

are also accountable for its performance. Further, the synergy between ZnO and TiO₂ materials would promote charge separation and minimize recombination, leading to higher degradation efficiency of the ZnO-TiO₂ composite [61].

The ability of ZnO to degrade MPs into non-toxic by-products is particularly advantageous for environmental remediation. ZnO photocatalysis largely mineralizes MPs to avoid secondary pollution, in contrast to traditional methods with harmful residues [62]. Moreover, the low energy needs of ZnO photocatalysis render it suitable for large-scale applications, furthering the practicality of such processes to mitigate microplastic pollution [63].

Despite its advantages, ZnO has several limitations that can affect its photocatalytic performance. Like TiO₂, ZnO primarily absorbs UV light, which limits its effectiveness under natural sunlight conditions. Although doping and composite strategies can improve visible light absorption, achieving efficient photocatalysis under visible light remains a challenge [64].

One of the greatest obstacles in ZnO photocatalysis is the fast recombination of photogenerated electron-hole pairs. This recombination results in fewer numbers of charge carriers for a redox reaction, leading to decreased overall photocatalytic efficiency [65]. Thus, modification strategies aimed at enhancing charge separation are essential to mitigate this issue.

Table 3. Performance of ZnO for the degradation of MPs.

Material	Reactor Type	Reaction Condition	Degradation Efficiency	Reference
ZnO nanorods	Batch Reactor	Visible Light Irradiation	High efficiency for LDPE degradation	[66]
ZnO-TiO ₂ composite	Batch Reactor	UV Light	Enhanced degradation due to synergistic effects	[61]
ZnO/Graphene oxide	Photocatalytic Reactor	Visible Light	Improved efficiency due to increased surface area	[67]
Self-Doped ZnO microrods	Batch Reactor	UV Light	High-temperature stability and effective degradation	[68]

2.3. Photocatalysts Other than TiO₂ and ZnO

MP degradation by other types of semiconductors photocatalysts, besides TiO₂ and ZnO, has become a focus of research in recent years. In this context, GO, WO₃, and CdS show great potential for this application. Additionally, next-generation materials like nanocomposites, hybrid materials, and MOFs have been reported to enhance photocatalytic performance towards MP degradation. In Table 4, these photocatalysts' performances of MP degradation are compared.

GO is a two-dimensional material composed of hybridized sp² orbitals, featuring a layered structure with hydrophilic oxygen functional groups on both the edge and basal planes. It can be used as an acceptor/transporter of photogenerated electrons to help separate photogenerated electron holes, improving photocatalytic activity. Uoginté et al. [28] investigated polyethylene decomposition and the photocatalytic efficiency of both GO and GO-TiO₂ composite.

WO₃ is another promising photocatalyst with a bandgap of approximately 2.7 eV, allowing it to absorb visible light. Its photocatalytic activity can be enhanced through various modification strategies, such as doping with metals or forming composites with other materials [38]. For instance, a hybrid heterojunction C₃N₄/WO₃ photocatalyst displayed greatly improved photocatalytic activity over its individual components, efficiently forming ROS crucial for MPs degradation [69].

The development of nanocomposites and hybrid materials that combine different photocatalysts can significantly enhance photocatalytic activity. For example, integrating ZnO with GO or other semiconductors can improve light absorption and charge separation, leading to enhanced degradation rates of MPs. Such hybrid systems leverage the strengths of each component, resulting in improved photocatalytic performance under various light conditions [70]. Zinc oxide nanoparticles, synthesized using an extract from the leaves of *Piper longum*, effectively degrade microplastics, with the most pronounced degradation observed at a concentration of 100 μL of ZnO nanoparticles. The optimal degradation occurs at a concentration of 75 μL [71]. The process of photodegradation of polypropylene plastic was conducted in aqueous solutions under atmospheric conditions and exposure to ultraviolet radiation, utilizing ZnO as a catalyst. The experiment lasted for 6 h at a temperature ranging from 35 and 50 $^{\circ}\text{C}$, resulting in an optimal degradation efficiency of 7.9% [72]. Tofa et al. investigated the photodegradation process of LDPE MPs residues using ZnO nanorods as a catalyst. The findings revealed the formation of various low molecular weight compounds, including peroxides, hydroperoxides, carbonyl, and unsaturated groups. Furthermore, researchers explored the effectiveness of plasmonic platinum-zinc oxide nanorods (ZnO-Pt) in enhancing the photodegradation of an LDPE film. The surface plasmon resonance effect of the platinum nanoparticles significantly enhanced the light absorption of the ZnO-Pt nanorods in the visible spectrum, while ZnO nanorods exhibited a strong affinity for UV light and a weaker affinity for visible light. Additionally, ZnO-Pt demonstrated a notable reduction in the recombination of photogenerated h^{+} and e^{-} compared to pure ZnO nanorod samples, as reported in reference [49].

A parallel study was conducted on the photocatalytic degradation of MP particles (MPs) in water using a catalyst based on bismuth oxychloride (BiOCl) under the irradiation of visible light. Jiang et al. [73] synthesized a novel, hydroxy-rich, ultrathin form of bismuth oxychloride, designated as BiOCl-X , for the degradation of high-density polyethylene MPs. After 5 h of reaction, the mass loss of the polyethylene MPs amounted to 5.4%, a figure that is 24 times greater than that achieved with BiOCl under identical reaction conditions. This phenomenon can be attributed to the increased number of surface hydroxyl groups present in BiOCl . These hydroxyl groups can generate more hydroxyl radicals ($\cdot\text{OH}$) when exposed to light [73].

Furthermore, incorporating metal nanoparticles like silver or gold alongside semiconductor photocatalysts can significantly boost photocatalytic performance through plasmonic effects, which enhance light absorption and promote charge transfer. These innovations in nanocomposite design play a vital role in developing more effective photocatalytic systems for microplastic degradation [74].

MOFs, or metal-organic frameworks, are highly porous crystalline materials that consist of metal ions coordinated with organic ligands. Their tunable structures, large surface areas, and strong pollutant adsorption capabilities make them promise for photocatalytic applications. Recent studies suggest that MOFs can serve as effective photocatalysts for degrading organic pollutants, including MPs, by promoting reactive oxygen species (ROS) generation under light irradiation. Their ability to enhance charge separation and provide extensive surface interactions further supports their potential in advanced photocatalytic systems [75,76]. The reactive oxygen species (ROS) generated by MOFs can be precisely controlled by modifying the MOF structure or altering environmental conditions, allowing for the selective and targeted degradation of microplastics. These ROS, manifested through hydroxyl radicals ($\cdot\text{OH}$), are generated through mechanisms akin to Fenton reactions. In such reactions, metal ions incorporated within the MOF act as catalysts, triggering the formation of ROS in the presence of oxygen and moisture [77,78].

In a recent study the zinc-based MOF $\text{Fe}_3\text{O}_4\text{-PVP@ZIF-6}$, exhibited remarkable catalytic activity in the oxidative degradation of Bisphenol F. The catalytic performance is attributed to the production of ROS in the presence of oxygen and moisture. ROS initiates the process of radical chain scission in polymer chains, leading to the fragmentation of MPs and their subsequent degradation into smaller molecular fragments [79].

The groundbreaking study is conducted on an innovative photocatalytic material, a heterostructure composite denoted as @, which is formed by the integration of pyromellitic diimide (PDI) with graphitic carbon nitride (g-C₃N₄). This specific combination, known as g-C₃N₄/PDI@MOF, where MOF stands for NH₂-MIL-53(Fe), exhibits remarkable properties in rapidly degrading water-soluble contaminants such as Bisphenol A (BPA) within just 30 min under visible light illumination [80].

Table 4. Performance of various photocatalytic materials for the degradation of MPs.

Material	Reactor Type	Reaction Condition	Degradation Efficiency	Reference
GO	Batch and continuous flow systems	Visible light irradiation	High efficiency in degradation of low-density polyethylene (LDPE)	[8]
WO ₃	Batch and continuous flow systems	Visible light irradiation at ~pH 6–7	60–90% for MPs (PS, PE) over extended periods (12–24 h)	[81]
Pt/ZnO	Photocatalytic reactor	A 50 W dichroic halogen lamp operating in atmospheric conditions, providing illumination in the visible spectrum (60 to 70 klux).	The VI and the CI increased by 15% and 13% for the LDPE fragments.	[66]
BiOCl-X	Photocatalytic reactor	Under the illumination of 250 W Xe lamp ($\lambda > 420$ nm) for 5 h.	5.38% for Polyethene MPs	[73]
$\text{Fe}_3\text{O}_4\text{-PVP@ZIF-67}$	Photocatalytic reactor	The catalyst concentration is $0.15 \text{ g}\cdot\text{L}^{-1}$, PMS concentration is 0.3 mM, and without pH adjustment for 60 min	99.8% BPF removal	[79]
g-C ₃ N ₄ /PDI@NH ₂ -MIL-53(Fe)	Photocatalytic reactor	30 min in the presence of H ₂ O ₂ and visible LED light ($420 < \lambda < 800$ nm)	Maximum efficiency of 100% (10 min) for bisphenol A (BPA)	[8]

2.4. Self-Propelled Photocatalytic Micromotors

Recently, self-propelled photocatalytic micromotors have aroused intense research interest as frontier technology for conventional photocatalytic systems to degrade microplastics (MPs) in aquatic solutions. Such micromotors provide a dynamic and self-powered approach that integrates photocatalytic reactivity with mobility to maximize the probability of the pollutant-catalyst contact, and to enhance degradation performance toward complex water matrices. In sharp contrast to the immobilized or suspended photocatalysts that mostly depend on the passive-diffusion process and encounter mass transfer limitations, micromotors can actively travel in polluted sites to find and degrade MPs, which could greatly enhance their meet-and-degrade ability toward MPs. This development is of high importance especially in the case of heterogeneous systems where MPs are separated and may have poor interaction with static catalysts.

Typically, these micromotors are made as Janus particles, which are asymmetrical micro-/nanostructures whose two faces are functionalized with different compounds. One side consists of a sunlight-sensitive photocatalyst such as TiO₂, and the other side

includes propulsion components such as platinum, silver, or magnetic components that make the microbots swim.

Upon illumination with an appropriate light source (usually UV or visible light), the photocatalyst produces photogenerated electron-hole pairs, which trigger redox reactions, resulting in the formation of reactive oxygen species (ROS) including hydroxyl and superoxide radicals. These radicals can degrade high-molecular-weight MPs polymer chain by chain, inducing breaking down and then mineralization of MPs [82]. Concurrently, microrotor propulsion is actuated through self-electrophoresis or diffusiophoresis. For self-electrophoresis, asymmetric ion flux distributions across a micromotor surface produce a local electric field which pushes the particle, whereas for diffusiophoresis, transport is driven by concentration gradients established during catalytic reactions. These activities can drive fast and directional motion in water environments, promoting catalyst dispersion and enhancing the contact between the micromotor and pollutants [83,84].

The motion of these micromotors leads to enhanced kinetics due to their mobility. Their active motility endows them with the ability to swim in stagnant or low-current areas otherwise difficult for standard catalysts to reach. This increase in mass transfer rate accelerates the rate of reaction and the possibility of micromotors to self-propel within the bulk of the water being treated, achieving effective self-distribution in regions that are near and far from the light source, leading to a more homogeneous environment of degradation.

In addition, micromotors may disturb the boundary layers of MPs, allowing for a more effective penetration of ROS to the polymers. Several studies have also reported the higher efficiency of micromotors when compared with static systems [85,86]. For instance, TiO_2/Pt Janus micromotors have been reported to realize effective suspended matter, mainly microplastics and organic pollutants, removal under visible light. In the first, magnetically maneuverable TiO_2 micromotors were able to “shovel” microplastics into close contact with catalytic surfaces, accelerating their decomposition. Some other designs have added doping or compositing to enhance visible light absorption and stability, and they have broadened the applications beyond laboratory settings [82].

Nevertheless, self-propelled micromotors still suffer from several obstacles that hinder their practical applications in real environmental conditions at the large-scale level. The manufacture of micromotors typically involves advanced techniques such as physical vapor deposition (PVD) or microfluidic synthesis, which are costly and difficult to scale [83]. Moreover, the service-life endurance of micromotors can be challenging in the active surfaces degradation, particularly in very challenging conditions like wastewater or natural waters. Photocatalytic activities and propulsion efficiencies of NPs may also be lowered by the fouling from natural organic matter (NOM) or/and the competitive adsorption of the non-target species [87]. Furthermore, questions regarding the environmental safety of leftover micromotors, especially comprising noble metals or synthesized polymers, need to be answered before widespread use. Approaches including biodegradable micromotors and magnetically recoverable micromotors are being investigated to overcome these risks and promote environmental sustainability [88].

In a nutshell, self-propelled photocatalytic micromotors present an attractive and advanced strategy for the degradation of microplastics in aquatic environments. Their self-propelled motility, improved interaction with pollutants, and compatibility with real-world conditions confer a significant advantage over passive photocatalytic systems. Nevertheless, in order for these concepts to be practically applied outside of proof-of-principle work, it is necessary for future development to provide solutions for scalability, cost, long-term stability, and environmental considerations. Materials engineering, green synthesis, and reactor integration will be crucial in bringing micromotor technology from lab demonstration to field-applicable tools for addressing the global problem of microplastic pollution.

3. Mechanisms of Photocatalytic Degradation of MPs

The adsorption of MPs onto photocatalyst surfaces is a critical factor influencing the efficiency of photocatalytic degradation processes. Two primary factors that govern this adsorption are the surface area of the photocatalyst and its chemical affinity for MPs. The surface area of a material is a crucial factor in the process of adsorption. The larger the surface area of a photocatalyst, the more active sites it provides for the adsorption of MP particles, resulting in enhanced degradation efficiency. Hierarchical structures like TiO₂ nanoflowers, for instance, show excellent photocatalytic activity as they increase surface area, allowing closer interaction with pollutants, including MPs [89]. Similarly, increased surface area and efficient sunlight interaction of plasmonic reactions in nanocomposites have also been observed to accelerate the degradation of MP fragments, indicating the role of the reactive species formed during degradation [49].

Chemical affinity is another crucial factor influencing adsorption. The interaction between the photocatalyst and MPs can be significantly affected by the surface chemistry of the photocatalyst. For example, the presence of functional groups on the photocatalyst surface can enhance their affinity for MPs, leading to improved adsorption and subsequent degradation [7]. Studies have demonstrated that the modification of photocatalyst surfaces can optimize their chemical properties, thereby increasing their effectiveness in adsorbing MPs [13]. Furthermore, the adsorption behavior is strongly dependent on the MP type and environmental condition, suggesting that both the chemical nature of the photocatalyst and the MPs are crucial to the adsorption process [90].

Moreover, the interaction between MPs and photocatalysts is not solely dependent on physical adsorption; it also involves chemical interactions that can lead to the degradation of the MPs. For instance, the photocatalytic degradation of low-density polyethylene (LDPE) using zinc oxide nanorods was shown to be effective, with the degradation process being facilitated by the chemical affinity of the photocatalyst for the MP [49]. This highlights the importance of both surface area and chemical affinity in optimizing photocatalytic systems for the removal of MPs from aquatic environments.

The generation of ROS, particularly hydroxyl radicals ($\cdot\text{OH}$) and superoxide radicals ($\text{O}_2^{\cdot-}$), plays a pivotal role in the photocatalytic degradation of MPs. These radicals are important to help depolymerize complex polymer structures into smaller, manageable fragments, for these compounds to be mineralized into non-toxic byproducts.

Hydroxyl radicals ($\cdot\text{OH}$) are among the most potent oxidants generated during photocatalysis. They are produced through the reaction of photogenerated holes (h^+) with water or hydroxyl ions present in the solution [91]. The high reactivity of $\cdot\text{OH}$ allows it to attack various organic compounds, including MPs, leading to oxidative degradation. For example, studies have shown that the presence of hydroxyl radicals significantly enhances the degradation rates of MPs, as they can cleave the carbon-carbon bonds within the polymer chains. Moreover, the generation of $\cdot\text{OH}$ can be influenced by various factors, including the type of photocatalyst used and the environmental conditions, which can affect the overall efficiency of the degradation process [92].

Superoxide radicals ($\text{O}_2^{\cdot-}$) also contribute to the photocatalytic degradation of MPs. These radicals are formed when electrons (e^-) generated during the photocatalytic process react with molecular oxygen (O_2) [93]. The superoxide radicals can further react with water to produce hydrogen peroxide (H_2O_2), which can subsequently decompose into hydroxyl radicals [18]. This cascade of reactions highlights the interrelated roles of different ROS in stimulating the degradation of the MPs. The generation of superoxide radicals has been demonstrated to enhance the degradation of organic pollutants, including MPs, through its contribution to subsequent oxidation reactions [94].

The efficiency of ROS generation and their subsequent reactions can be influenced by the photocatalyst's properties. For instance, modifications to the surface of photocatalysts, such as doping with metals or nonmetals, can enhance the separation of photogenerated charge carriers, leading to increased production of $\cdot\text{OH}$ and $\text{O}_2^{\cdot-}$ [95]. Additionally, the choice of photocatalyst material, such as titanium dioxide (TiO_2) or silver phosphate (Ag_3PO_4), can significantly impact the types and amounts of ROS generated during the photocatalytic process [96].

The photocatalytic degradation of MPs is a complex stepwise pathway comprising the photocatalytic oxidation and scission of the polymer chains, the formation of intermediate degradation products, and finally, complete mineralization into CO_2 , water, and non-toxic residues (Figure 2). All these steps are crucial to comprehend how photocatalytic processes can reduce the environmental risk associated with MPs. The steps are as follows:

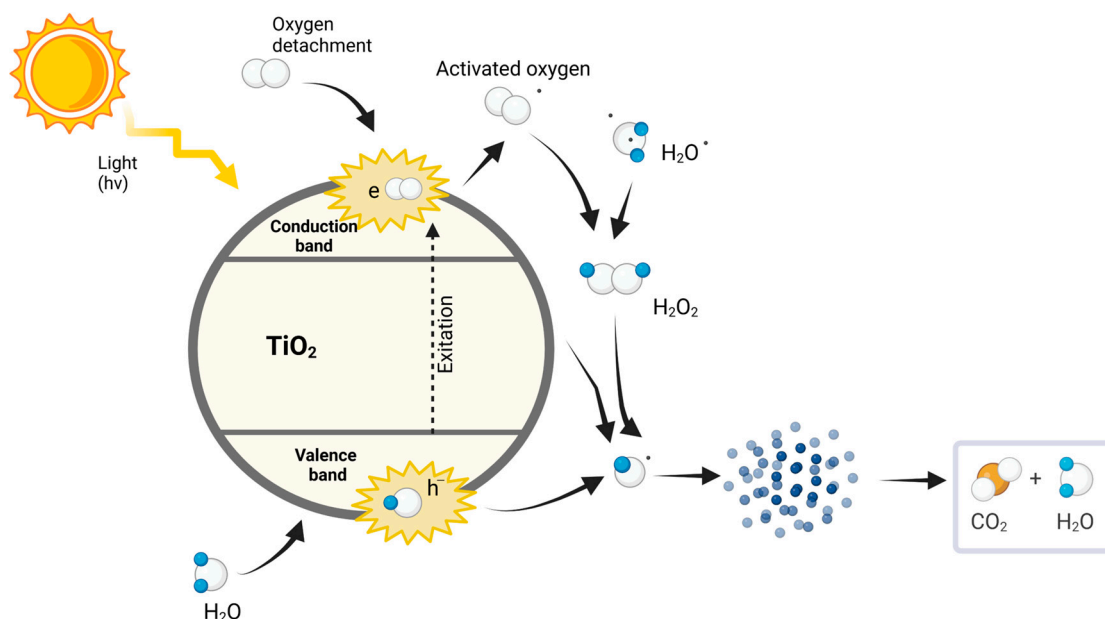


Figure 2. Photocatalytic degradation of MPs into non-toxic residues (CO_2 and water). Adapted after [97].

- (1) Photocatalytic oxidation and scission of polymer chains: The initial step of the photocatalytic degradation of MPs is achieved through the oxidation of polymer chains induced by ROS produced during the photocatalytic process. When exposed to UV light, photocatalysts, such as titanium dioxide (TiO_2) or ZnO , create electron-hole pairs, which can react with water and oxygen to form hydroxyl radicals ($\cdot\text{OH}$) and superoxide radicals ($\text{O}_2^{\cdot-}$) [18,98]. These radicals are highly reactive and initiate the oxidation of the polymer chains, resulting in scission, which splits the long-chain polymers into smaller fragments [99]. At the solid–solid interface between photocatalyst and MP, this process is highly efficient as it favors charge separation and avoids charge carrier recombination [18].
- (2) Formation of intermediate degradation products: As the polymer chains are cleaved, various intermediate degradation products are formed, including oligomers and monomers. These intermediates can vary in size and chemical structure, depending on the type of MP and the specific conditions of the photocatalytic process [100]. As an example, recent studies have demonstrated that the fragmentation of high-density polyethylene (HDPE) MPs has been accompanied by the generation of oligomers, which, under prolonged photocatalytic action, were converted into even smaller monomers [76]. The formation of these intermediates provides insight into the ef-

iciency of the degradation process and the potential for complete mineralization, making their identification and characterization critical.

- (3) Complete mineralization into CO₂, H₂O, and non-toxic residues: The final step in the photocatalytic degradation pathway is the complete mineralization of the degradation products into harmless byproducts such as CO₂ and H₂O. This process involves further oxidation of the intermediates, which can be facilitated by the continued presence of ROS [101,102]. For instance, under optimal conditions, polystyrene photocatalytic degradation can achieve complete mineralization, where the residual products are completely converted to gaseous CO₂ and liquid H₂O, and leaving no toxic residues [103]. The mineralization efficiency can be influenced by various factors, including the type of photocatalyst used, the intensity of light, and the presence of additional oxidants [11].

The observed differences in photocatalytic performance among materials such as TiO₂ and ZnO can be attributed to variations in their fundamental mechanisms for generating ROS critical to MP degradation. TiO₂, with a bandgap of 3.0–3.2 eV, and ZnO, around 3.2 eV, primarily absorb UV light, which limits their natural sunlight applications due to minimal visible light activity. However, doping or combining with other compositions such as activated carbon can improve visible light absorption, hence enhancing photocatalytic efficiency [11,104]. Another critical issue that governs the efficiency of ROS production in these semiconductors is the electron-hole recombination which is reduced by some modifications such as composite formation with GO or by metal (silver, indium) doping in order to produce a higher number of ROS required for the effective MP degradation [40]. Moreover, nanostructured configurations of TiO₂ nanoflowers or ZnO nanorods displayed much larger surface areas, which is important for adsorption processes and a key factor in maximizing photocatalytic interaction with MP pollutants [105]. Tailored strategies for ROS generation combine with these structural properties to optimize degradation rates toward specific types of MPs, connecting photocatalytic performance to the composition and morphology of the material [104,105].

4. Factors Affecting Photocatalytic Degradation of MPs

Various factors play a significant role in influencing the photocatalytic degradation of MPs, including the wavelength and intensity of light used, pH and temperature, catalyst concentration, and the unique properties of the MPs, such as type and size. Understanding these factors is essential for optimizing photocatalytic processes aimed at mitigating microplastic pollution. Table 5 provides a summary of these factors and their effects.

Table 5. Summary of factors influencing photocatalytic degradation.

Factor	Effect on Photocatalytic Degradation	Key Considerations
Light wavelength	- Shorter wavelengths (e.g., UV light) enhance photocatalytic activity due to higher energy availability for electron excitation. - Visible light activity can be improved by doping photocatalysts to extend absorption.	- UV light offers high efficiency but limited natural availability - Doping (e.g., N-doping) expands utility under visible light.
Light intensity	- Higher intensity increases ROS generation, enhancing degradation. - Excessive intensity can lead to light scattering and reduced effective reaction zones.	Optimal light intensity must balance ROS generation and light penetration.

Table 5. Cont.

Factor	Effect on Photocatalytic Degradation	Key Considerations
pH	- Affects surface charge of the photocatalyst (e.g., TiO₂ has a PZC at pH 6–7). - Adsorption efficiency varies with pH due to changes in charge interaction between catalysts and MPs.	Acidic pH often enhances adsorption and degradation of MPs. Adjust pH based on pollutant and catalyst properties.
Catalyst dosage	Increasing concentration increases active sites but beyond a threshold leads to diminishing returns due to light scattering and reduced light penetration.	Identify optimal concentration to maximize efficiency while minimizing scattering effects.
Type of MPs	- Functional groups and chemical structure influence interaction with photocatalysts and degradation pathways. - Certain plastics yield more toxic byproducts.	Evaluate compatibility between microplastic type and photocatalyst. Consider the environmental impact of degradation byproducts.
Size of MPs	- Smaller MPs degrade more efficiently due to higher surface area-to-volume ratio and better adsorption onto photocatalyst surfaces. - Larger particles require longer exposure or more aggressive conditions.	Tailor photocatalytic setup based on particle size distribution in the polluted water.
Temperature	Higher temperatures can increase reaction rates but may also deactivate the catalyst or accelerate undesirable side reactions.	Maintain moderate temperature to balance activation energy and catalyst stability.
ROS	ROS generation (e.g., hydroxyl radicals) is critical for breaking down MPs. Efficiency depends on factors like light intensity, pH, and catalyst properties.	Optimize system for maximum ROS generation while avoiding unwanted reactions or secondary pollution.

Photocatalysts, such as TiO₂, are traditionally activated by UV light, which has a shorter wavelength and higher energy, allowing for effective excitation of the photocatalyst [106]. However, the efficiency of photocatalytic processes can vary significantly with different wavelengths. Studies have evidenced that the shorter the irradiation wavelengths (such as those present in the UV range), the higher the photocatalytic activity associated with these mechanisms, due to the amount of energy available for the excitation of electrons [106]. For example, it showed that the photocatalytic degradation of organic pollutants was more effective under shorter wavelengths, which was associated with enhanced ROS generation [106]. Conversely, visible light photocatalysis has gained attention due to its potential for utilizing solar energy. Modifications to photocatalysts, such as doping with nitrogen or other elements, can extend their absorption spectrum into the visible range, thereby enhancing their photocatalytic activity under sunlight [107,108]. reported that N-doped SnO₂/TiO₂ photocatalysts exhibited improved photocatalytic activity due to their ability to absorb light at longer wavelengths (up to 409.2 nm) [108]. This indicates that the design of photocatalysts to absorb visible light can significantly enhance their applicability in real-world scenarios where UV light is not readily available.

Photocatalytic efficiency is also affected fundamentally by light intensity. Similarly, higher light intensities can accelerate the formation of reactive oxygen species (ROS), leading to enhanced degradation of MPs [106]. However, beyond a given threshold, more intense light may result in light scattering and smaller effective reaction zones, lowering the

overall MPs degradation rate [109]. It has been shown that photocatalytic activity of TiO_2 is strongly influenced by the cut-off wavelength, with degradation rates varying widely depending on the illumination conditions [18].

In practical applications, the light source type and its wavelength could significantly affect the degradation efficiency of MPs. It has been reported that the mineralization efficiency of MPs is far greater when the photocatalyst is at the solid-state and directly on the MPs under UV light, in comparison to when it is in a suspended liquid phase [18]. This emphasizes the importance of optimizing light conditions to enhance the interaction between the photocatalyst and MPs.

The surface charge of TiO_2 is highly dependent on the pH of the solution. The photocatalyst can change its charge at different pH, and thus, exhibits different affinity towards MPs. TiO_2 typically exhibits a point of zero charge (PZC) around pH 6–7, meaning that below this pH, the surface becomes positively charged, and above it, negatively charged [18]. Since MPs are often hydrophobic compounds that can interact with the photocatalyst differently depending on system pH, such charge variation can be a serious factor in affecting the adsorption of these compounds. At lower pH levels, the enhanced positive charge on the TiO_2 surface can increase the adsorption of negatively charged MPs, thereby improving degradation efficiency [98].

Previous research has shown that for photocatalytic degradation processes, there is often an optimal pH range. For example, it was shown that the imazapyr degradation rate by photocatalysis decreased as pH increased, indicating that an acidic pH improved the degradation rate [110,111]. Similarly, it has been shown that the degradation of polyethylene terephthalate (PET) MPs is highest under pH at about 2.1, where maximum free radical generation occurs [111]. These results emphasize the need for a better understanding of the pH conditions to optimize the activity of photocatalytic systems.

Thus, in practical applications, manipulating the pH of the reaction medium is a simple way to promote photocatalytic degradation of MPs. Acidic or neutral pH conditions can promote the adsorption of MPs onto the photocatalytic surface and enhance the generation of reactive species, raising the efficiency of degradation processes [112]. Moreover, the influence of pH on other factors, such as light intensity and catalyst loading, needs to be considered to establish a systematic method for optimizing photocatalytic systems.

The concentration of the photocatalyst typically has a direct relationship with the rate of photocatalytic degradation. As the concentration of the catalyst increases, the number of available active sites for the adsorption of MPs also increases, which can enhance the degradation efficiency [113]. For instance, Priyanka et al. found that maximum dye degradation was observed at a catalyst dosage of 1.5 g/L, indicating that an optimal concentration can significantly improve the photocatalytic performance [113]. Similarly, it was noted that the degradation rate constant should increase linearly with catalyst concentration, provided that other factors remain constant [114]. However, at some point, higher catalyst concentration can decrease the overall efficiency of the photocatalytic process. At high concentrations, light scattering may occur, leading to less effective penetration of light through the reaction medium [115]. This process could inhibit photocatalyst activation and ROS production required for the degradation process. For instance, it has been emphasized that although the relationship between catalyst mass and initial reaction rates is linear, the use of higher catalyst concentrations above a certain limit does not result in significant improvements in degradation efficiency [116]. This suggests that an optimal catalyst concentration must be established to balance the availability of active sites with the need for effective light penetration.

Determining the optimal catalyst concentration is essential for maximizing photocatalytic efficiency. Studies have shown that while increasing catalyst concentration can

enhance degradation rates, there is often an optimal point beyond which further increases do not yield significant benefits. For instance, it has been demonstrated that the photocatalytic degradation of methyl orange dye is most efficient at a specific catalyst loading, beyond which the efficiency begins to decline due to light scattering effects [112]. This aligns with findings from other studies, which suggest that the optimal catalyst concentration varies depending on the specific photocatalytic system and the nature of the pollutants being degraded [117,118].

More importantly, catalyst concentration is a crucial factor to consider for improving the photocatalytic degradation of MPs in practical application. This may provide a larger amount of adsorption of MPs onto the catalyst surface and more ROS generation, eventually leading to high degradation rates [118]. By analyzing its correlation with other operational parameters like light intensity and pH, we can tune these factors to achieve a more efficient photocatalytic system to deal with MPs pollution.

The chemical structure of the MPs also plays a crucial role in determining the efficiency of photocatalytic degradation. For example, the presence of functional groups in certain types of MPs can enhance their interaction with photocatalysts, leading to improved adsorption and subsequent degradation [100]. Furthermore, degradation pathways may differ widely between distinct types of MPs, leading to varying toxicities of degradation byproducts released in the surrounding microenvironment [119]. A range of additives is added to plastics in their manufacture to improve their resistance to erosion or heat, and these can reach the environment as the materials degrade. For example, MPs from polyvinyl chloride (PVC) have been reported to leach bisphenol A (BPA) during the anaerobic digestion process, which has endocrine-disruption activity [120,121].

The size of MPs is another critical factor affecting degradation efficiency. Smaller MP particles generally have a higher surface area-to-volume ratio, which can enhance their interaction with photocatalysts and increase the availability of active sites for degradation reactions [72]. For instance, research has indicated that smaller MPs can be more effectively degraded due to their increased adsorption capacity on photocatalyst surfaces, leading to higher rates of ROS generation and enhanced degradation efficiency [74]. Conversely, larger MP fragments may require longer exposure times or more aggressive photocatalytic conditions to achieve similar degradation efficiencies, as their larger size can hinder effective contact with the photocatalyst [122].

5. Photocatalytic Reactor Designs for Microplastic Degradation

The degradation of MPs through photocatalytic processes can be effectively facilitated by various reactor configurations, including slurry reactors, fixed-bed reactors, and immobilized photocatalysts. Each configuration presents unique advantages and challenges that can influence the efficiency of MP degradation.

Reactor design plays a crucial role in determining the photocatalytic performance of different materials and mechanisms by affecting light penetration, mass transfer, and catalyst recovery. In slurry reactors, photocatalysts are suspended in the solution, maximizing light exposure and promoting better contact with MPs, which enhances degradation rates. However, the difficulty in recovering the photocatalyst can limit reusability. Fixed-bed reactors, where the photocatalyst is immobilized, simplify recovery and reuse but may suffer from mass transfer limitations and uneven light distribution, particularly with larger particles or high flow rates. Immobilized systems provide stability and reusability for materials like TiO_2 , though reduced surface area and possible hindrance of light penetration can decrease degradation efficiency.

Reactor design also influences the specific performance of photocatalytic materials; for example, magnetic photocatalysts can be easily recovered in slurry reactors, while

immobilized systems may offer better long-term use, albeit with lower initial degradation rates. Thus, optimizing reactor design is essential for balancing light absorption, mass transfer, and catalyst recovery to improve the overall efficiency of photocatalytic degradation processes.

Slurry reactors are commonly used in photocatalytic processes due to their ability to maintain a homogeneous mixture of photocatalysts and MPs in a liquid medium (Figure 3). In this configuration, the photocatalyst is suspended in the reaction mixture, allowing for effective light penetration and interaction with MP particles. The schematic illustration of photocatalytic slurry reactor depicted in Figure 3.

The dynamic nature of slurry reactors facilitates the continuous mixing of reactants, which can enhance the contact between the photocatalyst and MPs, leading to improved degradation rates [123]. However, slurry reactors also face challenges, such as the difficulty in recovering and reusing the photocatalyst after the reaction. The separation of the photocatalyst from the treated water can be cumbersome, often requiring additional filtration or centrifugation steps [123]. Despite these challenges, slurry reactors are advantageous for large-scale applications where continuous operation is desired, and they can achieve high degradation efficiencies for various types of MPs [123].

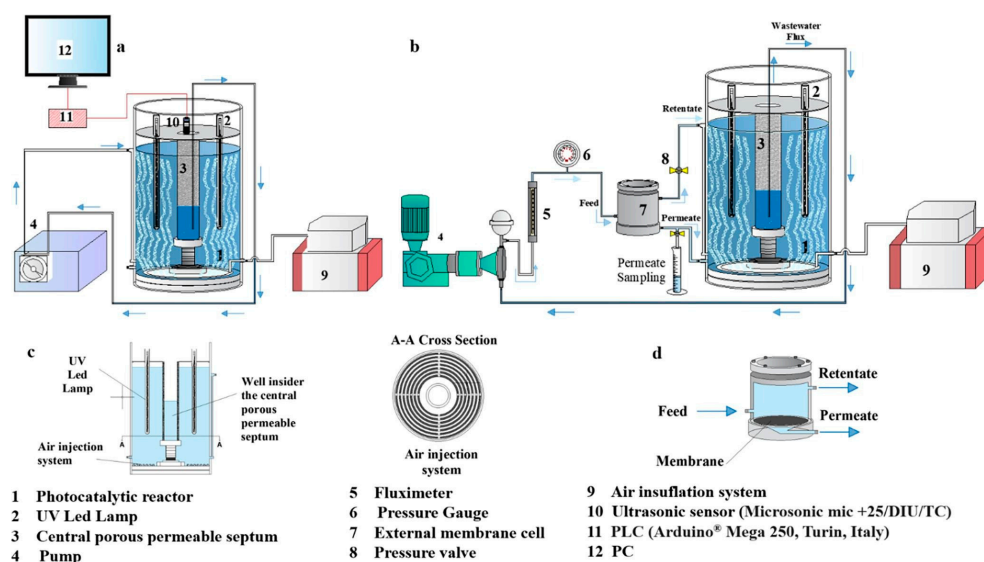


Figure 3. Scheme of photocatalytic slurry reactor. (a) configuration used in the hydraulic and photocatalytic preliminary tests; (b) complete slurry PMR configuration; (c) air injection system and cross-section; (d) cell containing the membrane. Adapted from [123].

Fixed-bed reactors involve the immobilization of photocatalysts in a packed bed configuration, where the MPs flow through the reactor (Figure 4). This configuration provides a simpler route for photocatalyst separation since it is immobilized during the reaction. A packed, fixed-bed configuration can benefit the interaction between MPs and the photocatalyst since MPs are compelled to flow over the catalyst surface and, thus are likely to undergo effective degradation [124]. In general, the packing density of the catalyst and the flow rate of the MP-laden solution can be factors affecting the efficiency of fixed-bed reactors. The bigger the packing densities, the larger the surface area for the reactions, but an optimal flow rate is required to maintain the time of contact between the MPs and the photocatalyst [125]. However, the fixed-bed reactors are susceptible to mass transfer limitations, especially for large MPs or when the flow has a high rate, which causes low degradation efficiency [126].

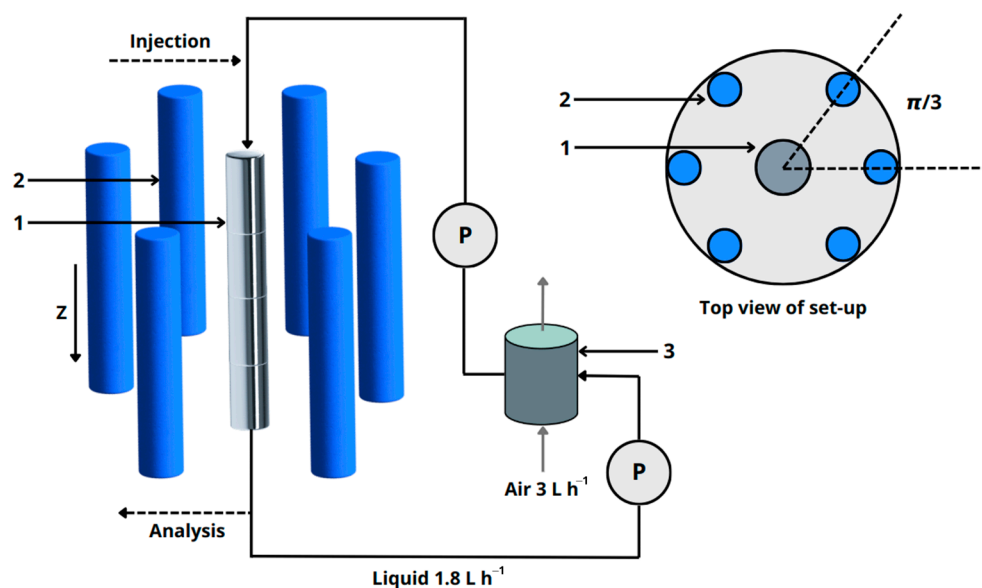


Figure 4. Experimental fixed bed photocatalytic reactor filled with TiO₂-coated media: (1) fixed bed reactor, (2) lamps, and (3) tank. Reproduced from [127].

Cloteaux et al. [127] conducted a study on a fixed-bed photocatalytic reactor equipped with TiO₂-coated media as depicted in Figure 2, for the purpose of wastewater treatment. The media employed were Raschig rings and the illumination source was provided by UV-A lamps. The analysis of the fluid dynamics within the reactor in the present study is predicated upon a conceptual framework that incorporates a temporal residence distribution model encompassing aspects such as light distribution, chemical kinetics, and material transfer. This framework, when integrated with the Langmuir–Hinshelwood (L-H) kinetics model, enables precise characterization of alterations in the concentration levels of contaminants at the reactor exit.

Immobilized photocatalysts are photocatalytic materials that are fixed on a support structure to facilitate the handling and recovery of the photocatalysts following the degradation process. This setup is adaptable in slurry and fixed-bed reactors. Immobilization can improve the stability and reusability of photocatalysts and is notably essential for the economic viability of photocatalysts in real-world applications [18,128].

The immobilization of photocatalysts can also influence their activity. For instance, the surface area and porosity of the support material can affect the adsorption of MPs and the generation of ROS [129]. Studies have shown that immobilized photocatalysts can achieve comparable or even superior degradation efficiencies compared to suspended photocatalysts, particularly for certain types of MPs [11,130]. However, the choice of support material and the method of immobilization are critical factors that can impact on the overall photocatalytic performance.

The optimization of photocatalytic processes for MP degradation can be significantly enhanced through various strategies aimed at improving light penetration, catalyst recovery, and reusability. Light penetration is crucial for effective photocatalysis, as it directly influences the generation of ROS necessary for degrading MPs. Several strategies can be employed to enhance light penetration:

The utility of light can be greatly enhanced by the development of photocatalysts that can absorb light in a wider range, especially in the visible and near-infrared (NIR) regions. For instance, the incorporation of MOFs on modified nanocrystals has been shown to enhance NIR-driven photocatalytic activity, allowing for better light absorption and subsequent degradation of pollutants [131].

The design of photocatalytic reactors can also be optimized to improve light distribution. For example, hierarchically structured porous materials are used to increase light scattering and enhance light harvesting, thus improving the photocatalytic efficiency [132]. Moreover, continuous flow reactors have better light penetration than batch reactors, ensuring more even exposure of the photocatalyst to light [133].

The thickness of immobilized photocatalyst films can be optimized to balance light absorption and penetration. Research has indicated that increasing the thickness of photocatalytic films up to an optimal value can enhance reaction rates due to improved light absorption [134]. However, excessive thickness may hinder light penetration, so careful optimization is necessary.

The ability to recover and reuse photocatalysts is essential for the economic viability of photocatalytic processes. Several strategies can enhance catalyst recovery and reusability:

- (1) Immobilizing photocatalysts onto support materials can facilitate easy recovery after the degradation process. This approach not only simplifies the separation of the catalyst from the reaction medium but also enhances the stability and reusability of the photocatalysts [135]. For instance, immobilized TiO₂ photocatalysts have shown promising results in terms of reusability without significant loss of activity [135].
- (2) The development of magnetic photocatalysts allows for easy separation using external magnetic fields. This method has been successfully applied to various photocatalytic systems, enabling efficient recovery and reuse of the catalyst [134].
- (3) Enhancing the properties of photocatalysts, such as their surface area and porosity, can improve their performance and longevity. For example, the introduction of oxygen vacancies on TiO₂ surfaces has been shown to enhance photocatalytic activity and stability, contributing to better reusability [136].
- (4) Implementing these optimization strategies can lead to significant improvements in the efficiency of photocatalytic degradation of MPs. By enhancing light penetration, photocatalytic systems can achieve higher degradation rates, while effective catalyst recovery and reusability can reduce operational costs and environmental impact.

Scalability is still one of the most important issues that limit the broad application of photocatalytic methodology for water treatment. Of the reported reactors, immobilized photocatalyst systems and fixed-bed reactors have the most practical potential for large applications because they can be reused, are structurally stable, and are well-adapted to continuous flow operation [127]. Although slurry reactors are efficient at the lab scale, they generally suffer due to catalyst recovery and catalyst fouling, potentially increasing operating costs [9].

Self-propelled micromotors offer a very innovative and efficient solution for improved MP contact and degradation, specifically under stagnant or low-flow scenarios. However, their scalability is limited by the high synthesis cost, the complexity of the fabrication process (e.g., physical vapor deposition), and the possible environmental issue of residual nanomaterials [137,138]. Consequently, they are currently more appropriate for specialized or regional use rather than widespread implementation. In cost-efficiency comparisons, the traditional methods to remove microplastics (e.g., filtration, sedimentation, flotation) are usually cheap but inefficient (especially for the removal of nano- and micro-sized particles [139]). The photocatalytic systems, especially systems with visible-light-active and immobilized catalysts, present a trade-off between economic benefit and much higher degradation efficiency as well as the possibility of full mineralization [140]. When combined with solar energy or low-energy lighting sources, these systems can add more savings to energy and enhance sustainability. Consequently, hybrid systems integrating photocatalysis with other separation and/or recovery technologies are developing as a potentially economically feasible solution for large-scale MP remediation [141].

6. Current Challenges and Limitations of Photocatalytic Degradation of MPs

The stability and reusability of photocatalysts are critical factors that influence the overall efficiency and economic viability of photocatalytic degradation processes. Many photocatalysts (e.g., TiO_2), are known for their high photocatalytic activity; however, they can suffer from degradation or leaching over time, which can reduce their effectiveness [141]. For example, studies have shown that although TiO_2 nanoparticles are able to mineralize MPs, their activity decreases after prolonged use, possibly due to agglomeration and loss of surface area [142]. Additionally, the stability of photocatalysts can be influenced by the operation conditions, including light intensity and reactive components. Extended exposure to UV light could result in the occurrence of photo corrosion or structural alterations in the photocatalyst, causing a drop-in catalytic activity [142]. Therefore, developing photocatalysts that maintain their structural integrity and activity over multiple cycles is essential for practical applications. Recent advancements in hybrid photocatalytic systems, such as those combining biotic and abiotic components, have shown promise in enhancing stability and reusability, as evidenced by those who reported improved mineralization efficiency with their hybrid system [142].

The potential generation of undesired by-products during the degradation process of photocatalytic degradation is another major issue. Although the aim of photocatalysis is to mineralize MPs to harmless end products such as CO_2 and water, the incomplete degradation of MPs results in the formation of intermediate products that can be toxic and/or environmentally persistent [142]. The degradation process of polystyrene (PS) MPs, for example, has been linked to the generation of different types of organic compounds [143] some of which are harmful to aquatic environments. The types and amounts of by-products formed can vary considerably depending on the nature of the photocatalyst and the operational parameters. For instance, some photocatalysts may lead to the generation of certain intermediates, while others may facilitate complete mineralization [143]. Monitoring and characterization of these by-products are fundamental to accurately evaluating the overall environmental impact of photocatalytic processes. Optimizing reaction conditions, e.g., pH and light intensity, has been shown to be effective in reducing the formation of harmful by-products and improving the overall degradation efficiency [144].

Most common photocatalysts are only activated by UV light, which limits their activity under visible light conditions. However, despite improvements to TiO_2 allowing for enhanced activity within the visible light spectrum (such as through metal or non-metal doping), most modified photocatalysts maintain their activity at levels significantly below their UV-active counterparts [142,145]. For instance, while some studies have reported improvements in photocatalytic activity under visible light, the overall degradation rates for MPs remain suboptimal, often requiring prolonged exposure times to achieve significant degradation [98,145]. Moreover, the photonic energy conversion efficiency of photocatalytic systems under visible light is typically not sufficient. Although modified photocatalysts may absorb visible light, this does not always lead to efficient charge separation and the generation of reactive oxygen species (ROS), both of which play important roles in the degradation of MPs [145]. In many cases, incomplete degradation causes the intermediate to accumulate; this may bring on new risks for the environment [146].

Given the limitations of current photocatalytic systems, there is a pressing need to develop photocatalysts that can efficiently utilize solar light for the degradation of MPs. Solar energy is abundant and represents a sustainable energy source for photocatalytic processes. However, the challenge lies in designing photocatalysts that can effectively absorb and convert solar energy into the necessary reactive species for degradation [147,148].

Recent research has focused on the development of hybrid photocatalytic systems that combine different materials to enhance light absorption and energy conversion. For example, the integration of plasmonic materials with traditional photocatalysts has shown promise in improving visible light absorption and enhancing photocatalytic activity [143]. Moreover, the application of bio-derived photocatalysts based on bio-based materials has been investigated to enhance solar light harvesting and minimize the ecological footprint of photocatalytic reactions [11]. Furthermore, optimizing reactor designs to maximize light exposure and improve mass transfer can also contribute to more efficient energy conversion in photocatalytic systems. Continuous flow reactors and innovative light delivery systems can enhance the interaction between MPs and photocatalysts, leading to improved degradation rates [11,15].

7. Conclusions

Photocatalytic removal of MPs is a novel and eco-friendly method for the solution of wide existent MP pollution. This comprehensive review highlights the various photocatalytic materials, mechanisms, and challenges associated with the degradation of MPs in both aquatic and terrestrial environments.

TiO₂ and ZnO emerge as the most extensively studied photocatalysts due to their high activity in generating ROS, which are crucial for breaking down MPs into smaller, less harmful compounds. However, both materials primarily function under UV light, which constitutes a minor portion of the solar spectrum. Efforts to enhance their activity under visible light through doping and the creation of composites have shown some success, but achieving efficient photocatalysis under natural sunlight remains a challenge.

The generation of ROS, including hydroxyl radicals and superoxide anions, plays a pivotal role in the photocatalytic degradation of MPs. These radicals are effective in initiating the breakdown of polymer chains, leading to the formation of smaller fragments. The goal is the complete mineralization of MPs into benign substances such as carbon dioxide and water. However, achieving full mineralization is complex, as incomplete degradation can result in the formation of toxic by-products, which pose additional environmental risks. One of the key challenges in this process is ensuring the stability and reusability of photocatalysts, such as TiO₂ and ZnO. These materials often face issues such as charge carrier recombination, which reduces their catalytic efficiency over time. Moreover, operational parameters such as light intensity and pH can significantly affect the stability and performance of photocatalysts, prompting further investigation into more robust and durable materials. The design of reactors also plays a crucial role in optimizing the efficacy of photocatalytic reactions. Slurry reactors and immobilized photocatalyst systems offer distinct advantages and challenges regarding catalyst recovery and scalability. Slurry reactors enable continuous operation but present challenges in catalyst recovery, whereas immobilized systems facilitate easier catalyst recovery but may experience reduced catalytic activity due to reduced surface area interaction with MPs.

Despite the advancements in photocatalytic degradation, several challenges remain. The formation of undesirable by-products during the degradation process and the limited effectiveness of photocatalysts under visible light hinder the widespread application of this technology. There is a need for the development of novel materials that can efficiently utilize solar light, as well as hybrid systems that combine different catalytic mechanisms to enhance overall efficiency.

Moreover, future research must address several practical challenges to bridge the gap between laboratory-scale success and field-scale application. The efficient recovery and reuse of photocatalysts remain significant bottlenecks, particularly when using nanoparticulate forms that are difficult to retrieve from treated water. The development of magnetically

separable or immobilized catalysts may offer viable solutions, provided they maintain catalytic performance across multiple reuse cycles. Equally critical is the scalability of photocatalytic systems under natural sunlight. Environmental factors such as turbidity, light scattering, and varying irradiance limit the effectiveness of solar-driven systems. Research into solar-reactor designs that maximize photon capture and ensure efficient mass transfer is essential to improve performance under real-world conditions. Other emerging technologies, which potentially address mass-transfer limitations and enhance the interaction between pollutants and catalysts, are represented by the use of micromotors or self-propelled photocatalytics; however, their environmental fate, production cost, and long-term stability in natural waters are still questioned. Despite some emerging techniques, the expensive advanced materials, such as metal–organic frameworks and noble metal composites, limit the popularization of this method. Attention should be paid to the development of inexpensive congener photocatalysts with highly efficient and environmentally friendly features. At the same time, the development of multifunctional materials that are able to degrade MPs and co-contaminants could improve the efficiency and applicability of the techniques.

Finally, thorough toxicological investigation of degradation intermediates is required urgently. While photocatalysis aims to convert MPs to end products that are harmless, the intermediate forms may remain or present new ecological hazards. Advanced analytical methods and environmental bioassays should be added to future work to evaluate the safety of both catalysts and their degradation pathways. By providing solutions to these practical and environmental aspects together, the field may move closer to a set of scalable and ecologically friendly photocatalytic methods to tackle microplastics.

In conclusion, while photocatalysis holds significant potential for addressing the environmental threat posed by MPs, ongoing research is essential to overcome the technical challenges associated with this technology. Future efforts should focus on enhancing the performance of photocatalysts under visible light, improving the reusability and stability of these materials, and developing reactor designs that maximize degradation efficiency while minimizing the formation of harmful by-products. With continued innovation, photocatalytic degradation could become a key tool in mitigating the global problem of MP pollution.

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