Narrative Review Article

# Microplastic Degradation: Interplay Between Photoaging, Photocatalytic Degradation, and Periphytic Biofilms

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## ABSTRACT

Microplastics (MPs) are pervasive in aquatic environments and pose significant ecological and health concerns. Considerable attention has been given to the process and methods for reducing and degrading MPs. Many studies focus on the processes separately, and few mention the combined effect of MP degradation. This review evaluates two key methods of MP reduction, photodegradation under sunlight and microbially mediated biodegradation, and highlights the role of periphytic biofilms in modulating these processes. Photoaging, driven by UV radiation and reactive oxygen species (ROS), changes MP surface chemistry, morphology, and fragmentation behavior in ways that depend on polymer type, pigment, and environmental condition. Conversely, biodegradation involves microbial and biofilm-mediated conversion of MPs into simpler compounds, with rates that are influenced by polymer chemistry, community composition, and environmental factors. Recent studies reveal that biofilms can inhibit MP photoaging by shielding particle surfaces from UV light, while also altering microbial community composition, MP surface properties, and degradation kinetics. Despite advances in understanding mechanisms of biofilm colonization, photoaging, and biodegradation independently, their coupled effects remain poorly characterized. A deeper understanding of biofilm–MP–light interactions is essential for developing conceptual models and sustainable remediation strategies to mitigate plastic pollution in aquatic ecosystems.

**Keywords:** Microplastics; Photoaging; Photocatalysis; Periphytic biofilms; Biodegradation; Aquatic ecosystems; Plastic pollution

## INTRODUCTION

Microplastics (MPs), defined as plastic fragments that are smaller than 5mm, are ubiquitous pollutants in aquatic and atmospheric environments (1). MPs not only absorb chemical pollutants but also leach additives into water bodies, thereby exacerbating contamination. Approximately 54.5% of oceanic MPs are polyethylene (PE), 16.5% are polypropylene (PP), with the remainder comprising polyvinyl chloride (PVC), polystyrene (PS), polyester, and polyamides (PA) (2). MPs have been detected across multiple trophic levels, from zooplankton to mammals, posing serious ecological and health risks (Figure 1). Laboratory exposure studies indicate that high concentrations of MPs can trigger immune responses, oxidative stress, and reproductive or developmental toxicity in aquatic organisms (3). Human exposure via ingestion, inhalation, and dermal contact is also of concern, as MPs have been associated with inflammatory

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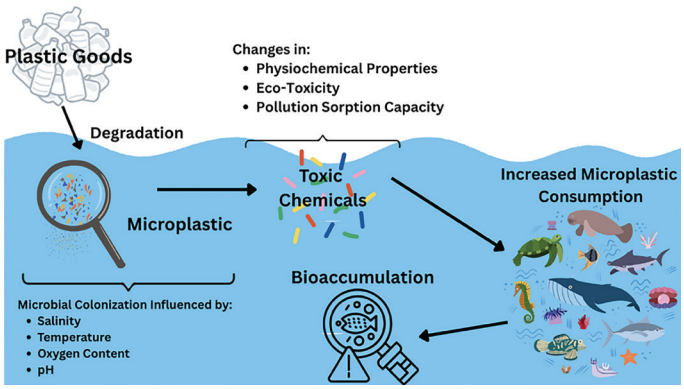


***Figure 1.*** *Schematic representation of MP degradation, microbial colonization, and ecological impacts in aquatic environments. MPs are formed from plastic goods colonized by microbes that are influenced by various factors. The result is the pollution of toxic chemicals in aquatic environments, which are then consumed by aquatic animals. Redrawn from (6).*

responses and other adverse health indicators in some studies (4, 5).

Periphytic biofilms, complex microbial communities of bacteria, algae, and fungi, readily colonize MPs in the aqueous environment, altering their physical, chemical, and biological properties. Such colonization can physically degrade polymer surfaces, alter crystallinity and hydrophobicity, and influence pollutant adsorption capacity (6-10). Biofilm abundance generally increases with exposure time but declines with water depth (10). Additionally, variations in microbial community structure can influence MP buoyancy, determining whether particles float or sink (11).

Another factor influencing MP fate is photoaging, the weathering and degradation of plastics under ultraviolet (UV) radiation, primarily driven by reactive oxygen species (ROS) (12). Susceptibility varies across polymers: PS and PVC, containing benzene rings or C-Cl bonds, are particularly prone to photoaging, often showing yellowing of surfaces (13). Photoaged PS MPs can release organic (toxic, smaller, more oxidized) and inorganic (heavy metal ions and anions) compounds, raising environmental concerns like water contamination, ecosystem toxicity, and bioaccumulation (14).

Photocatalysis, an eco-friendly degradation approach, employs sunlight and a catalyst, such as titanium dioxide ($TiO_2$), zinc oxide (ZnO), or iron-doped $TiO_2$, to accelerate MP breakdown (15). The efficiency of photocatalytic degradation depends on multiple factors, such as catalyst type, light source, solution pH, temperature, and the size and shape of the MPs. While photocatalysis shows promise for mitigating MP risks, extended treatment times (2 weeks of visible light exposure) are often required to achieve substantial removal (16).

Despite advances in understanding photoaging and biodegradation independently, little is known about how biofilms modulate MP degradation under UV exposure. Biofilm formation may change the surface roughness, surface chemistry, and microbial community structure, thereby influencing MP photooxidation dynamics (17). To date, many studies have examined biodegradation and photooxidation as separate processes. A key knowledge gap remains in understanding how biofilm colonization interacts with photocatalysis degradation under varying UV wavelengths, hydraulic conditions, and growth media (18).

This review aims to collate current knowledge on the interplay between biofilms and MP photoaging and to explore strategies for reducing MPs in aquatic environments. Specifically, this paper analyzes the mechanisms of photoaging processes, examines biodegradation mediated by biofilms, and evaluates the influence of biofilms on MP photoaging. The review also identifies critical research gaps and highlights the future directions for developing effective strategies to remove MPs in aquatic systems.

## PHOTOAGING PROCESSES OF MICROPLASTICS

Photodegradation broadly refers to the breakdown of compounds through the absorption of high-energy photons. A major sub-process, photooxidation, involves chemical reactions between UV radiation, oxygen, and the polymer matrices, producing ROS. The presence of ions, natural organic matter, and minerals can accelerate ROS generation, thereby enhancing photooxidation (19).

Photoaging of MPs can be divided into direct and indirect pathways. In direct photoaging, ultraviolet light (290-400 nm) breaks the weak surface bonds of polymers. Indirect photoaging occurs when chromophores within polymers absorb photons, generating ROS and initiating bond cleavage, such as C-H scission. UV exposure also catalyzes the release of dissolved organic matter from MPs and accelerates additive leaching. For example, PS exposed to UV can release phthalates (a common plasticizer), while PE may release $TiO_2$ particles (21).

The extent of photoaging is strongly influenced by polymer type, photocatalyst use, and even surface color.

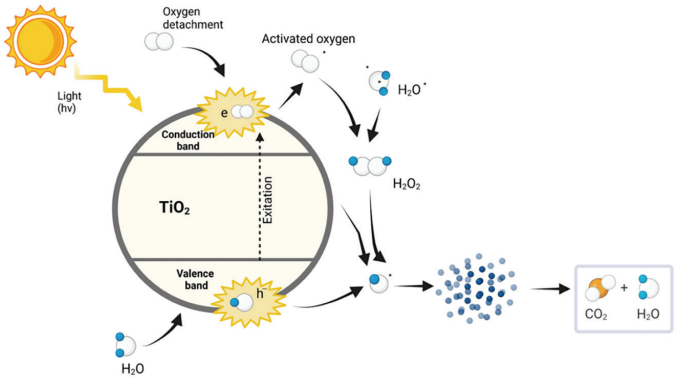


*Figure 2. Mechanism of $TiO_2$-mediated photocatalytic degradation in aqueous environments. Light excitation promotes electrons from the valence band to the conduction band, creating holes that react with $O_2$ and $H_2O$ to generate ROS, which oxidize pollutants to $CO_2$ and $H_2O$. Adapted from (20).*

## Photocatalysis

Heterogeneous photocatalysis, the acceleration of photoreaction in the presence of a catalyst, has emerged as a promising MP degradation strategy. This approach was pioneered in 1972 with the discovery of $TiO_2$-driven water splitting (22). Under controlled laboratory conditions, photocatalytic systems can substantially accelerate surface oxidation and fragmentation of certain MPs, although their effectiveness varies with polymer type, catalyst properties, and light conditions. $TiO_2$ is widely applied as a photocatalyst because it generates ROS when activated by UV light (Figure 2). Doping, adding another element or compound, can also shift its bandgap to harness visible light. $TiO_2$-based films, particularly Triton X-100, induced morphological changes and size reduction in PS within just 3 hours (23).

ZnO, another common photocatalyst, enhances brittleness and surface oxidation in low-density PE films (24) but has limitations due to narrow UV absorption and potential nanoparticle leaching. Recent work integrates ZnO with plasmonic metals to boost visible-light absorption and oxidative efficiency (16).

## Polymer Susceptibility

Photoaging susceptibility varies among polymers. Aromatic polymers such as PS and polyurethanes are highly vulnerable due to their complex chemical structures, leading to greater fragmentation and discoloration under UV irradiation (25, 26). In contrast, low-density PE and polyamide 6 show intermediate susceptibility, while PP exhibits relatively low degradation rates. This is because PP's compact structure resists UV degradation, whereas low-density PE allows greater oxidation (25).

## Color Effects

Color also modulates photoaging. A comparative study of colored PE MPs (transparent, yellow, red, orange, green, blue) found that colored MPs degraded faster than transparent ones, with yellow and red MPs, having longer-wavelength pigments and higher lightness, showing greater photoaging than blue or green MPs (27). MP pigmentations more susceptible to UV light had a higher photoaging degree, as shown in Figure 3. UV light exposure leads to progressive color fading, increased photooxidation, and polymer chain breakdown (27). This indicates that pigmentation can significantly alter UV absorption and degradation dynamics.

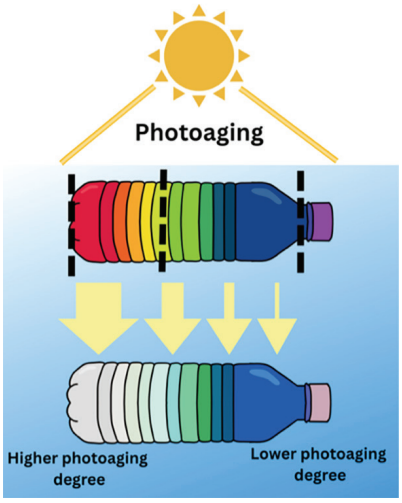


*Figure 3. An illustration of photoaging under UV light. The schematic highlights the variations in degradation rates depending on different color pigments. Yellow and red MPs show a higher degree of photoaging compared to green and blue MPs. Redrawn from (27).*

# BIODEGRADATION AND BIOFILM-MEDIATED DEGRADATION

Polymers are broadly classified as biodegradable or nonbiodegradable compounds. In the case of biodegradable polymers, biodegradation is a process in which microorganisms such as algae, bacteria, and

fungi convert plastic polymers into microbial biomass, gases, and organic compounds. Biodegradation proceeds through biodeterioration, biofragmentation, depolymerization, assimilation, and mineralization (28). Examples of biodegradable polymers include Polycaprolactone, Polylactide, and Polybutylenadipate terephthalate, whereas non-biodegradable polymers include PS, PVC, and Polyamide 66.

Although the size and density of the plastics influence their settling behavior, the presence of biofilms on the surface does not significantly alter settling velocity, meaning that biodegradability does not necessarily guarantee faster removal from aquatic systems (29). Other environmental factors, pH, temperature, nutrient availability, and polymer-microbe surface compatibility, also regulate degradation rates (30).

### Role of Bacterial Microorganisms

Bacterial colonization is a major determinant of MP biodegradation. Microorganisms attach to substrates depending on their hydrophilic or hydrophobic surface properties: hydrophobic bacteria adhere more readily to hydrophobic plastics, while hydrophilic bacteria preferentially colonize hydrophilic surfaces (28). Certain strains have demonstrated the ability to degrade recalcitrant polymers. *Brevibaccillus borstelensis* reduced the gravimetric and molecular weights of PE by 11 and 30%, respectively, after 30 days of incubation (31). These effects are mediated through the secretion of enzymes that cleave polymer chains (32). However, laboratory-scale experiments often report limited efficiency: for example, *Bacillus* species produced measurable but insufficient weight loss to be considered scalable for real-world applications (33).

### Role of Biofilms

Biofilm formation further enhances the biodegradation potential of microorganisms. Biofilms act as facilitators by concentrating microbial activity on plastic surfaces, increasing enzyme efficiency and producing biosurfactants that enhance plastic-microbe interactions (34). In addition, biofilm-associated microbes can secrete lipophilic pigments that contribute to the discoloration and structural weakening of plastics (35). Although many bacterial species degrade MPs at relatively low efficiency, for example, PE only achieved a 1% weight loss after 30 days of incubation with Kocuria palustris M16, colonization is typically rapid, and marine environments contain abundant plastic-degrading bacteria (36).

Well-designed microbial consortia hold promise for improving degradation performance. Nutrient supplementation can further enhance biodegradation rates by stimulating enzyme production. For example, microbial communities supplemented with nutrients demonstrated a 13-fold increase in hydrocarbon-degrading enzyme activity (37). Thus, combining biofilm-based strategies with optimized environmental conditions may significantly improve the biodegradation efficiency of MPs in aquatic systems (17, 38).

## BIOFILM EFFECT ON MICROPLASTIC PHOTOAGING

Within the literature, few studies systematically compare biofilm growth with UV exposure methods, chemical and/or optical properties of growth media, surface characteristics, UV wavelengths, light penetration within biofilms, and hydraulic conditions during growth and exposure (18). Some experiments report that as biofilms mature, increased thickness and biomass enhance protection against UV stress, leading to higher apparent UV resistance in mature communities (39, 40). In contrast, other work shows that, as biofilms age, changes in extracellular polymeric substances (EPS), a protective layer surrounding microbial cells, can weaken their structural integrity and promote cell detachment, which may reduce resistance to physical and chemical stressors (41). In certain systems, these EPS changes and shifts in community structure have been interpreted as younger biofilms exhibiting greater resistance for specific endports than more mature biofilms (42). Taken together, these findings indicate that the effect of maturation on UV resistance is not universally defined; it likely reflects differences in microbial species and the community composition, biofilm thickness and architecture, irradiation wavelength and intensity, and the response measured in each experiment.

In a study of coastal wetland sediments, photoaging was reported as contributing to more than 55% of the total aging effect relative to biodegradation for select polymers (PP, PET, PLA), mainly because sunlight driven ROS inhibit microbial colonization (43). Experiments have shown that naturally produced ROS during sunlight exposure increase MP surface roughness and decrease particle size, supporting the conclusion that ROS are vital in sunlight-driven plastic degradation (44). However, biodegradation remains a crucial, more specialized, and slower method as it is highly contingent on polymer chemistry. Biodegradation was found to

be effective for biodegradable plastics like polylactic acid, where microbes such as *Arthrobacter oryzae* and *Bacillus* sp. played a larger role (43).

Biofilms impact photoaging with effects on UV irradiation. However, a recent study confirmed that biofilms inhibit the production of ROS by providing a higher resistance to MPs in natural water than in laboratory experiments when using pure MPs, therefore decreasing MP photoaging. Biofilms that absorb UV irradiation can change the photoaging of MPs. In Zhang et al.'s study, PPMPs and PSMPs were examined with filtered surface water from the Weihe River in Yangling, China, using UV lamps at different light intensities and incubated for different lengths of time. There was a pronounced biomass increase for PPMPs, but the opposite for PSMPs. In addition, more microorganisms were seen as the MPs aged, and their surface became rough near 105 days. The biofilm matrix is composed of EPS and contains chromophores that absorb UV photons and prevent the light from reaching the MP surface, shielding the plastic and reducing the generation of ROS that drives photoaging (45).

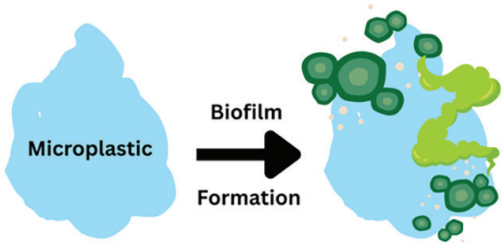


***Figure 4.*** *Illustration of biofilm formation on MP. Biofilms attach to the surface of MPs. Redrawn from (17).*

When biofilms form on the surface of UV-photoaged MPs (Figure 4) their characteristics undergo significant changes. Photoaging-induced ROS age the plastics and alter MP surface chemistry, which in turn modifies interactions with microorganisms rather than uniformly driving microbial dormancy (46). In early stages of incubation in soil, researchers found that because photoaging decreased the hydrophobicity of the MP, the biofilm biomass on original MPs was twice that on photoaged MPs. Photoaging also changed the genus level, a group of closely related bacterial species, of the bacterial composition and simplified and destabilized the bacterial plastisphere network, the ecosystem of microbes living on plastics (47). Although this study occurred in soil, the observed shifts in biofilm biomass and community structure provide insight to how photoaging may influence biofilm and MP interactions in other environments. Under simulated solar light irradiation, irradiated MPs can host environmentally persistent free radicals on their surfaces, which modify their redox behavior and have the potential to influence associated microbial communities and stress responses (48). The studies were conducted in terrestrial environments or laboratories, and additional work is needed to confirm how biofilm formation and photoaging affect MP microbe interactions in aquatic environments.

The key finding is that biofilms can slow down the photoaging process. Specifically, EPS absorbs UV irradiation, shielding the MP surface and preventing UV photons from reaching the plastic and inhibiting the generation of ROS. ROS production inhibits the initial microbial colonization and alters the community composition to ROS-resistant genera. Despite these findings, there are further unanswered questions that contribute to higher MP resistance in natural, biofilm-colonized environments compared to laboratory experiments.

## LIMITATIONS AND FUTURE PERSPECTIVE

Despite growing research, the understanding of how biofilms modulate MP photoaging remains limited. Most existing studies are short-term, laboratory-based, and use simplified microbial systems. First, few studies have measured how EPS thickness or biomass quantitatively alters UV transmission and ROS generation across polymer types. Laboratory conditions also rarely replicate fluctuating light spectra, temperature, or hydrodynamics of natural waters. In microbial community dynamics, the succession of biofilm communities under repeated light–dark cycles and nutrient gradients remain poorly characterized. Furthermore, integrated kinetic models combining photocatalytic and microbial degradation are scarce.

Future work should identify the dominant factors influencing aquatic MP photoaging, especially biofilm characteristics; quantify the extent to which biofilm presence reduces or modifies photoaging efficiency across different polymers and UV wavelengths; develop strategies to control or engineer biofilm formation to improve the degradation of MPs and support the development of effective mitigation technologies.

## CONCLUSION

This review synthesizes current understanding of microplastic degradation in aquatic systems through photocatalysis and biodegradation, emphasizing the mediating role of periphytic biofilms. Photocatalysis, particularly $TiO_2$- or ZnO-based processes, can accelerate surface oxidation and fragmentation of certain microplastics under UV exposure. However, relative degradation rates depend on polymer chemistry, catalyst properties, light spectrum, and environmental conditions. Biodegradation provides a complementary, biologically driven mechanism whose effectiveness is highly contingent on polymer type, microbial community composition, and the surrounding matrix. In many systems, photoaging contributes to microplastic aging and fragmentation, but biofilm presence can modulate degradation kinetics and mechanisms, and the relative importance of photoaging and biodegradation varies with polymer chemistry, environmental factors, and the outcome used to define degradation. Importantly, most available studies quantify degradation in terms of changes in surface chemistry, roughness, or particle size rather than complete mineralization. Therefore, particle size reductions do not necessarily represent environmental removal. Biofilms introduce additional complexity: while they facilitate microbial colonization and enzymatic activity, they can also attenuate UV radiation and suppress ROS formation, thereby slowing photoaging under certain conditions. To improve environmental relevance, future studies must integrate biofilm dynamics into experimental and modelling frameworks and develop hybrid approaches that couple abiotic (photooxidation, photocatalysis) and biotic (biofilmmediated biodegradation) processes, with explicit consideration of polymer chemistry, catalyst conditions, light spectra, microbial communities, and the environmental matrices in which microplastics reside.

## CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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