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Recent Studies on Chemical Degradation of Microplastics: A Review

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Abstract

The microplastic (MP) is a persistent contaminant that is commonly found in water, soil, sediments and air, and is less than 5 mm in size. This review aims to present the summary of recent studies concerning their chemical degradation, which include oxidative, photochemical, hydrolysis, advanced oxidation processes and free-radical. It also discusses the factors that determine the degradation efficiency: polymer composition, pH, crystallinity, catalysts, UV intensity and dose of oxidants. Recent technologies such as Fenton and photo-Fenton oxidation, ozonation, hydrogen peroxide treatment, persulfate activation, photocatalysis and electrochemical oxidation are discussed and compared on the basis of species generated, applicable polymers, advantages, and disadvantages. These methods can speed up the chain scission and partial mineralisation, but some challenges are still left unsolved: incomplete degradation, toxicity of intermediates, recovery of catalysts, energy demand and scale-up. The use of recyclable catalysts, real-environment validation, standardised assessment methods, and integration with biological treatment to realize sustainable microplastic remediation at practical scales with minimal secondary pollution should be emphasised in future research.

Keywords; Microplastics; Chemical degradation; Advanced oxidation processes; Photocatalysis; Mineralisation

INTRODUCTION

Microplastics (MPs) are plastic particles under 5 mm in size, which are an increasing environmental problem due to their persistence, ubiquity and natural degradation resistance. Their compact size enables them to build up in a variety of ecosystems and come into contact with pollutants and living organisms, potentially harming the environment and human health. Plastic use and production are growing all over the globe, with the production of micro-plastics increasing in parallel, making management an urgent environmental concern [1].

Microplastic can be divided into primary and secondary microplastic based on their origin. Primary microplastics are intentionally produced in the micro size range, for use in cosmetics, as industrial abrasives, and as plastic pellets. Secondary micro plastics, on the other hand, are created by the breakdown of larger plastic items through weathering, mechanical abrasion and oxidation and ultraviolet (UV) radiation. The degradation processes slowly degrade the polymer chains so that small plastic particles are continuously released into the environment [2].

The most prevalent polymers identified as micro-plastics include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS) and polyvinyl chloride (PVC). This is because they are widely used in packaging, textiles, construction materials and consumer goods, leading to their widespread presence in the environment. Microplastics are found in marine and freshwater environments, agricultural soils, sediments, atmospheric dust and even in remote areas, highlighting their ubiquity in the world, with movement via water, wind and humans [3], [4].

The traditional physical extraction techniques rarely remove microplastics entirely and most of the time they merely move microplastics from one medium to another without breaking down the polymer structure.

Hence, development of effective degradation technologies is becoming a key necessity to reduce the persistence of microplastics [5]. These include, among others, degradation methods using chemicals, such as advanced oxidation processes, photocatalytic degradation, and catalytic oxidation, which enable the fragmentation of polymer chains into smaller molecules and the mineralization of the polymers, thereby providing promising solutions to combat the problem of microplastic pollution [6].

Chemical Degradation Mechanisms of Microplastics

One of the most promising methods for decreasing the persistence of microplastics is to chemically degrade the polymer structure, which would change rather than simply extracting plastic particles from the environment. Chemical degradation processes differ from physical ones because they fragment the polymer chains into smaller molecules and continue to mineralise them to CO_2, H_2O or other low molecular weight compounds. The efficiency of degradation is dependent on the polymer composition, crystallinity, molecular weight of polymer, reaction conditions and presence of catalysts and/or oxidising agent [7].

Oxidative degradation mechanisms

Oxidative degradation refers to the process by which a chain of polymers is attacked by oxygen or powerful oxidants, which causes scission of the polymer chains and generation of oxygen functional groups, oxygen carbonyls, and hydroxyls. Polyolefins, especially polyethylene (PE) and polypropylene (PP), are known to be sensitive to oxidation at high temperatures, UV light or catalytic conditions, leading to a gradual loss of mechanical property and fragmentation.

Hydrolysis of susceptible polymers

Condensation polymers containing hydrolysable ester or amide bonds are mainly subject to hydrolysis. A polymer like polyethylene terephthalate (PET) will slowly decompose with water, especially in high temperature, alkaline and/or acidic conditions, to form smaller oligomers and monomers. Non-polar polymers, e.g. PE and PP, do not have any hydrolysable functional group and thus show a limited hydrolytic degradation.

Photochemical degradation

When UV radiation creates the reactive intermediates in the polymer, it causes the polymer to degrade, this is known as Photochemical degradation. Sunlight exposure leads to bond cleavage, surface cracking and plastic becomes more brittle, which contributes to the fragmentation of plastics to micro- and nanoplastics. This also makes polymers more susceptible to subsequent chemical oxidation [8].

Advanced oxidation processes (AOPs)

Advanced oxidation processes are processes involving the production of highly reactive oxidising species, e.g. UV/H_2O_2, ozone, Fenton and photocatalytic processes. These processes generate hydroxyl (•OH) and sulfate ($SO_4^{\bullet -}$) radicals which can quickly break down polymer chains making AOPs an effective means of fast degradation of microplastics.

Free radical reactions

Most pathways of chemical degradation can be traced back to free radical reactions. Reactive radicals then remove hydrogens from polymer backbones, and set off chain reactions which cause oxidation and chain cleavage. The overall effect of these reactions is to decrease the molecular weight and increase the yield of more easily degraded (less persistent) plastics.

Table 1: Chemical Degradation Mechanisms of Microplastics

Degradation Mechanism	Main Reactive Species/ Conditions	Most Susceptible Polymers	Major Products/ Effects	Advantages	Limitations
Oxidative Degradation	Oxygen (O_2), ozone (O_3), H_2O_2, elevated temperature, UV radiation	PE, PP, PS	Carbonyl and hydroxyl groups, reduced molecular weight, fragmentation	Simple process; enhances further degradation	Slow under natural conditions; may produce oxygenated intermediates
Hydrolysis	Water, acids, alkalis, heat	PET, PLA, polyamides	Monomers, oligomers, lower molecular weight compounds	Effective for condensation polymers; environmentally compatible	Ineffective for polyolefins (PE, PP) due to lack of hydrolysable bonds
Photochemical Degradation	Sunlight, UV-A, UV-B, oxygen	PE, PP, PS, PVC	Surface cracks, oxidation products, micro- and nanoplastics	Utilizes solar energy; accelerates weathering	Slow; incomplete mineralisation; dependent on sunlight intensity

Advanced Oxidation Processes (AOPs)	•OH, $SO_4^{•-}$, UV/H_2O_2, O_3, Fenton reagent, photocatalysts	PE, PP, PET, PS, PVC	Chain scission, oxygenated intermediates, CO_2, H_2O (partial mineralisation)	High degradation efficiency; rapid reaction	High operational cost; catalyst recovery and energy requirements
Free Radical Reactions	Hydroxyl radicals (•OH), sulfate radicals ($SO_4^{•-}$), alkoxy radicals (RO•), peroxy radicals (ROO•)	Most synthetic polymers	Reduced molecular weight, oxidised polymer fragments	Fundamental mechanism in most chemical degradation methods	Difficult to control; may generate toxic intermediate products

Abbreviations: PE – Polyethylene; PP – Polypropylene; PET – Polyethylene terephthalate; PS – Polystyrene; PVC – Polyvinyl chloride; PLA – Polylactic acid; UV – Ultraviolet; AOPs – Advanced Oxidation Processes; •OH – Hydroxyl radical; $SO_4^{•-}$ – Sulfate radical.

Factors Influencing Chemical Degradation of Microplastics

Several chemical, physical and operational variables affect the efficiency of chemical degradation of micro-plastics and influence the degradation rate of polymer chain cleavage and mineralisation. The reactivity of polymers with various chemical species is highly dependent on polymer types and treatment conditions. It is vital to understand these factors in choosing appropriate degradation technologies and to optimize treatment efficiency [9].

- **Polymer composition:** The chemical structure of polymer has a significant impact on the degradability. Polymers with hydrolysable functional groups are more prone to chemical degradation than polyolefins (e.g., polyethylene, PE, and polypropylene, PP, which have chemically stable carbon–carbon backbones).
- **Crystallinity:** The accessibility of the active species to the polymer matrix is related to the polymer crystallinity. Highly crystalline polymers are more resistant and the amorphous regions are more susceptible to attack by oxidants and catalysts due to the compact molecules structure in the former.
- **pH:** The solution pH affects the generation of reactive species and the stability of catalysts. In general, the acidic conditions promote the formation of hydroxyl radicals, thus favouring the Fenton-based oxidation, while alkaline conditions favour the hydrolysis of ester-containing polymers like PET.
- **Catalyst:** Catalysts can increase the rate of degradation by producing ROS or reducing activation energy for chemical reactions. Semiconductor photocatalysts such as TiO_2 or ZnO show good activity to promote the oxidation of polymers under UV/visible illumination and hence are widely used.
- **UV intensity:** The intensity of ultraviolet (UV) directly affects the degradation by photochemical reactions. An increase in the UV causes a greater amount of reactive radicals to form, which leads to greater photo-oxidation and bond cleavage, which leads to higher rate of polymer chain fragmentation.
- **Oxidants:** Highly reactive hydroxyl (•OH) and sulfate ($SO_4^{•-}$) radicals are generated by strong oxidants, such as hydrogen peroxide, ozone and persulfate, which can attack polymer backbones. The rate and degree of degradation and mineralisation are primarily a function of their concentration and reactivity.

Recent Chemical Degradation Technologies and Their Performance

In recent years, the chemical treatment technologies have been significantly advanced and the degradation of micro-plastics has been accelerated by polymer chain scission and mineralisation. These involve the use of highly reactive oxidising species or catalysts which break down the persistent polymers into smaller, less hazardous compounds in comparison to natural weathering. They are affected by the kind of polymer, catalyst, oxidant dose and operating conditions [10].

Fenton and Photo-Fenton Oxidation: Ferrous ions (Fe^{2+}) and hydrogen peroxide (H_2O_2) are employed in the reaction to produce hydroxyl radicals (•OH) that rapidly oxidize polymer chains in the reaction. Photo-Fenton processes are based on the Fenton reaction and use UV or visible light, which keeps regenerating Fe^{2+} and enhances the production of radicals. The methods are shown to have improved degradation of polyethylene (PE), polypropylene (PP) and polystyrene (PS).

Ozonation: Ozone (O_3) is a strong oxidising agent which can oxidise polymer surfaces by direct oxidation and radical reaction. Ozonation adds functional groups containing oxygen, makes polymer chains weaker, and increases their sensitivity towards further degradation. In particular, it is useful for the pre-treatment of old microplastics.

Hydrogen Peroxide Oxidation: Hydrogen peroxide is a very commonly used compound because it generates hydroxyl radicals with UV, heat or catalysts. It is an environmentally friendly oxidant because it does not produce chlorinated by-products, but encourages oxidation of polymer backbones.

Persulfate Activation: Activated persulfate produces highly reactive sulfate radicals ($SO_4^{\bullet -}$), which have high oxidation potential and have longer lifetimes than hydroxyl radicals. The degradation efficiency is enhanced by thermal, UV, transition metal or alkaline activation, especially for chemically stable polymers like PE and PP.

Photocatalysis Using TiO_2, ZnO and Other Semiconductor Catalysts: The photocatalysts are semiconductors, like titanium dioxide (TiO_2), zinc oxide (ZnO) and graphitic carbon nitride ($g\text{-}C_3N_4$), which upon illumination under light produce electron–hole pairs that lead to the formation of reactive oxygen species, which cause oxidation of polymer chains. Photocatalysis is one of the most promising methods for the sustainable remediation of microplastics, with high degradation efficiency and reusability of the catalyst [11].

Electrochemical Oxidation: In electrochemical oxidation, microplastics are destroyed by creating hydroxyl radicals and other types of reactive oxidants at the electrode surface without the need for a significant amount of chemical reagents. The approach is able to provide precise operational control and has minimal secondary waste, but energy use is a challenge for large scale use.

Table 2: Comparison of Recent Chemical Degradation Technologies for Microplastics

Technology	Primary Reactive Species	Typical Catalysts/ Reagents	Suitable Polymers	Major Advantages	Main Limitations
Fenton / Photo-Fenton Oxidation	•OH radicals	Fe^{2+}/H_2O_2, UV light	PE, PP, PS	High oxidation efficiency; rapid degradation	Requires acidic pH; iron sludge generation
Ozonation	O_3, •OH	Ozone gas	PE, PP, PET	Effective surface oxidation; good pre-treatment	High ozone demand; incomplete mineralisation
Hydrogen Peroxide Oxidation	•OH radicals	H_2O_2, UV or heat	PE, PP, PET	Environmentally friendly; easy operation	Often requires catalyst or UV activation
Persulfate Activation	$SO_4^{\bullet -}$, •OH	Persulfate, heat, UV, Fe^{2+}	PE, PP, PS	Strong oxidising ability; longer radical lifetime	Higher chemical cost; optimisation required
Photocatalysis (TiO_2, ZnO, $g\text{-}C_3N_4$)	•OH, $O_2^{\bullet -}$	Semiconductor photocatalysts	PE, PP, PET, PS	Reusable catalysts; solar-light utilisation	Catalyst recovery and light penetration limitations
Electrochemical Oxidation	•OH and active oxidants	Boron-doped diamond, Ti-based electrodes	Various polymers	No chemical addition; low secondary pollution	High energy consumption; electrode cost

Challenges, Environmental Impacts, and Future Perspectives

There have been recent advances in chemical degradation technologies that have shown great promise in reducing microplastic pollution. But there are still some technical, environmental and economic issues that hinder their widespread adoption. Solving these problems is crucial to allow degradation processes to be effective and environmentally friendly.

Challenges

Chemical degradation is a factor that can increase the rate of degradation of polymer chains, but under real conditions complete mineralisation is seldom realised. In partial degradation, intermediate oxidation products, such as low molecular weight organic compounds, aldehydes, ketones and carboxylic acids are often formed, some of which have not been fully understood in the environment. Further, many oxidation processes are very demanding in terms of energy input, use of expensive oxidants or special catalysts, which increases the cost of operation. The de-activation, recovery and re-use of catalyst is also another important challenge, especially for those catalysts containing nanoparticles like TiO_2, ZnO, etc. Also, degradation efficiencies obtained in laboratory conditions are often different from those found in natural waters or soils, due to the presence of natural organic matter, suspended matter and different pH in the soil and water, which may affect oxidation reactions [12].

Environmental Impacts

Chemical degradation normally decreases the persistence of micro-plastics through breaking the polymer chain into smaller components. However, the incomplete degradation can create nanoplastics or reactive intermediates which can be more mobile and potentially more toxic than the original microplastics. If not managed properly, residual catalysts and oxidants can impact aquatic organisms as well. It is important, therefore, to have extensive testing of the degradation products and their ecological effects prior to large-scale environmental use [13].

Future Perspectives

Further studies are needed on designing technologies for the degradation that will not lead to secondary pollution of the environment, and will be energy efficient. Hybrid systems combining advanced oxidation processes (AOP) with biological degradation can be considered as opportunities, because the chemical oxidation can enhance the ability of polymers to be degraded, followed by mineralisation by microorganisms. It is also necessary to give more attention to materials that are more responsive to visible light, to materials that can be recycled, to pilot scale validation in real environmental conditions and to standardised evaluation procedures for degradation efficiency and by-product toxicity. The growth of these technologies will help to develop more sustainable and viable ways to deal with microplastic pollution [14].

Literature review

(Hossen et al., 2026) [15] integrates mechanistic insights, performance measurements, and environmental consequences to critically assess current developments in these systems. Reactive oxygen species (ROS) and carbon-centered radicals are produced by photolysis using light, and ROS generation is increased by photo-Fenton and photocatalytic systems through cooperative chemical and light-driven processes. Recent innovations include the complete degradation of PVC under visible light-driven photocatalysis processes and the 100% mineralization of polystyrene nanoplastics within minutes utilizing photoelectro-Fenton. Co-factors that encourage ROS production and surface oxidation, including "inorganic minerals, organic acids, and halogen species", further boost the effectiveness of these reactions. Notwithstanding these developments, there are still significant obstacles to overcome, such as partial mineralization, the possibility of hazardous intermediate generation, catalyst recyclability, inconsistent methodology, and scaling constraints. Clarifying degradation processes, creating value-added and selective conversion strategies, creating green-synthesized catalysts that respond to visible light, incorporating biological systems, and standardizing analytical procedures are all important areas for future study.

(Kamalasekaran & Sundramoorthy, 2026) [16] gives a thorough summary of the methods currently used to look into the origins, distribution, toxicological effects, contamination, and biodegradation processes of microplastics in complicated environmental matrices. The growing promise of electrochemical sensing technologies as inexpensive, effective tools for detecting and categorizing microplastics is highlighted. Research on electrochemical sensors for microplastic monitoring is noticeably lacking, despite the increased interest in the electrochemical remediation of microplastics. The comprehensive comparison and critical assessment of several electrochemical sensing techniques for microplastic detection is the work's innovative methodology. Based on the most recent research, this analysis compares their respective benefits, drawbacks, and applicability to traditional detection techniques. Additionally, this paper provides a comprehensive analysis of electrochemical sensor construction strategies, including recognition components, sophisticated immobilization methods, and limit of detection protocols that are tailored for microplastic detection applications.

(Yadav et al., 2025) [17] investigates how different microorganisms, such as bacteria, fungus, and algae, may break down MPs through enzymatic activities, reducing the pollutants' half-life. The effectiveness and limits of microbial biodegradation are demonstrated by a thorough analysis of the degradation mechanisms of widely used polymers including "polyethylene, polystyrene, and polyvinyl chloride". The total weight loss rate of MPs is still rather low, usually ranging from 0 to 15%, despite the promise potential of some strains. This calls for more research into improving enzymatic activity and environmental circumstances. Technological developments in metagenomics and enzyme engineering provide strategies to improve degradation efficiency, with the potential to reach up to 90% degradation in 10 hours under ideal circumstances. This study emphasizes the necessity of thorough investigation to pinpoint the important microbial strains and enzymes involved, comprehend their degradation routes, and look at how various environmental matrices affect biodegradation processes.

(Yousafzai et al., 2025) [18] gives a comprehensive summary of current developments in MP detection and elimination, emphasizing both analytical and remedial technology. More accurate MP detection, quantification, and characterization—especially at the nanoscale—have been made possible by advancements in spectroscopic, thermal, and imaging-based approaches. To lessen MPs' negative effects on the environment, a number of degradation strategies have been created concurrently. These may be roughly divided into three categories: chemical, biological, and physical. Mechanical removal and heat processes like pyrolysis and thermal oxidation are examples of physical procedures. Advanced oxidation processes (AOPs) and photocatalysis, which uses semiconductors like titanium dioxide (TiO_2) to speed up polymer breakdown when exposed to light, are two aspects of chemical degradation. Enzymatic and microbial degradation are two biological methods that have demonstrated encouraging outcomes. The hydrolysis of ester and amide bonds in synthetic polymers is catalyzed by enzymes including PETase, MHETase, cutinases, lipases, and cellulases, providing specific and ecologically safe routes for the breakdown of microplastics. The review addresses the shortcomings and difficulties of existing technologies and delves deeper into the consequences of microplastic buildup, including bioaccumulation and oxidative stress in organisms.

(Zandieh et al., 2024) [19] The amount of plastic produced annually has increased in recent years, which has led to an increase in environmental problems, especially with regard to microplastics. The impact of plastic and microplastic waste on ecosystems and human health has become a major problem, calling for creative strategies. In this regard, catalytic degradation of microplastics becomes a crucial strategy with great potential for reducing the long-term consequences of plastic pollution. The present status of catalytic degradation of microplastics was critically examined in this study, along with the concept of degradation, methodologies for characterizing degradation products, and standards for standard sample preparation. Additionally, a summary is provided of the importance and efficiency of several catalytic entities, such as microbes, nanozymes, enzymes, and transition metal ions (for the Fenton reaction). Lastly, the catalytic degradation of microplastics is discussed, along with some important questions and future directions.

(Sutkar et al., 2023) [20] Recent years have seen research on a number of strategies for treating MPs. This review discussed the current stage of development, relevant degradation mechanisms, and newly proposed MPs degradation strategies, including biotic and abiotic. There are limitations, benefits, and drawbacks specific to each method. As a consequence, the advantages and disadvantages of each method have been carefully considered. Based on the information gaps in the 109 published research publications that were analyzed, some suggestions for possible research directions have been made. These include the absence of standardized methods for "assessing and quantifying the degradation process, degradation pathway analysis, and field application". The objective of this review is to provide a detailed description of the various MPs' disintegration processes, along with an overview of each one's benefits, drawbacks, and restrictions.

(Kinyua et al., 2023) [21] Numerous studies have demonstrated that since microplastics' functional groups interact and compound with heavy metals and persistent organic pollutants, they can acquire these chemicals as they move through the environment. Even while many microplastics may be significantly reduced by using standard wastewater treatment technologies, many still find their way into rivers and seas across the world through their effluents. Photocatalysis is one of the potential methods for cleaning wastewater. Despite the fact that it has shown tremendous promise for microplastic degradation, the majority of experiments are currently conducted in laboratories and must be expanded for practical use. Understanding the kinetics and rate of degradation is essential to estimating the technology's capital cost for real-world application. A number of operational factors, including surface area, temperature, the effect of pH, and light, must be optimized in order to scale up the method. Several developed photocatalysts for the degradation of microplastics are examined in this study. Analyzing these factors will lead to a thorough understanding of the optimal variables for future designs of photocatalytic degradation of microplastic for industrial applications.

Conclusion

Chemical degradation is an attractive alternative to physical degradation for decreasing the environmental persistence of microplastics as it involves a chemical alteration of the polymer chains instead of simply shifting the particles from one medium to another. Chain scission and partial mineralisation can occur through oxidation, hydrolysis, photo-oxidation, advanced oxidation processes, and through radical mediated pathways. They are effective depending on the polymer composition, crystallinity, pH, type of catalyst, intensity of ultraviolet and concentration of oxidant. Fenton-based treatments, ozonation, hydrogen peroxide, persulfate activation, photocatalysis and electrochemical oxidation are technologies that have performed well in the lab, but which do not always achieve complete mineralisation. There is a possibility of nanoplastics or intermediates formed in the process of incomplete conversion, and these might be toxic or have unknown environmental fate. Other hurdles to scale up include high energy consumption, reagent costs, catalyst deactivation and the differences between laboratory and real environmental matrices. Further research is needed to integrate biological treatment with chemical oxidation, to design catalysts which can be used in the presence of light and can be reused, to test systems in representative waters and soils, and to standardise methods of assessing degradation, mineralisation and by-product toxicity. Incorporating such integrated strategies is crucial to sustainable microplastic remediation.

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