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The Photo-Fenton Method Aids Microplastic Degradation: Experimental Findings Highlight Significant Differences Among Plastic Types

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Abstract. This work addresses the critical issue of microplastic pollution, which poses severe environmental and health risks. This paper evaluates the degradation efficacy of Fenton-based methods on three common microplastics (LDPE, PP, and PVC) under varying conditions of acidity, iron concentration, and H~2~O~2~ dosage. Results indicate that Photo-Fenton degradation is highly effective for LDPE, while conventional and Photo-Fenton methods show promising results for PVC, depending on experimental settings. However, PP proves resistant to all Fenton-based treatments, likely due to its stable polymeric structure. These findings suggest that different microplastics respond uniquely to Fenton reactions based on chemical structure and physical properties, highlighting the need for tailored degradation approaches. The study also identifies the potential of Fenton-like methods, which offer advantages in acidic or strongly reductive environments. While Fenton-based methods show potential for LDPE and PVC degradation, their practical application requires consideration of economic viability, safety, and sustainability. This research provides significant insights into optimizing Fenton-based methods for environmental microplastic pollution control and identifies critical gaps in current technologies, offering a scientific basis for future advancements in microplastic degradation strategies.

Keywords: Microplastic Pollution, Health Risk, Fenton Degradation

1. Introduction

In recent decades, the global proliferation of microplastics—defined as plastic particles smaller than 5 mm in diameter—has emerged as one of the most pressing, cross-cutting environmental and public health challenges of the 21st century. These ubiquitous pollutants, originating from sources as diverse as the fragmentation of plastic waste, the shedding of synthetic textile fibers, and even everyday consumer products like chewing gum [1], have infiltrated nearly every ecosystem on Earth: from the sediment of the Mariana Trench (the deepest point in the ocean) to the ice of the Arctic and the peaks of the Himalayas. Their unique combination of environmental persistence (taking centuries to degrade) and bioaccumulation potential (building up in organisms across trophic

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levels) has raised urgent concerns about their long-term ecological disruption and poorly understood impacts on human physiology.

The pervasiveness of microplastics is astonishing. They have been detected in remote areas such as the Arctic ice and the Mariana Trench, as well as in our daily lives. For instance, a study [1] revealed that a single piece of chewing gum can release thousands of microplastic particles during mastication, with 94% of these particles shed within just 8 minutes. In addition, research has shown that disposable paper cups release tens of thousands of microplastic particles when filled with hot drinks. Bottled water is also a significant source, with an average of about 240,000 plastic particles per liter. Moreover, tea bags made of nylon 66 or polyester (PET) release an astonishing number of microplastic particles when steeped in hot water. Even cleaning sponges release a large number of microplastics when worn out, with 6.5 million microplastics released per gram of wear.

Environmental monitoring studies highlight the alarming extent of microplastic contamination. A comprehensive survey of China's surface waters [2] revealed that 79.7% of 1,331 sampling sites across the country showed measurable microplastic accumulation between 2016 and 2022. Although most (83.9%) were classified as low ecological risk, the imbalance in regional research — mainly concentrated in the Yangtze and Yellow River basins — indicates that the pollution status in many areas remains unknown. This geographic disparity underscores the need for more widespread monitoring to fully grasp the global scope of the issue. Microplastics have also been detected in the air we breathe: they can be generated from the natural degradation of plastic items in daily life, as well as from the shedding and fragmentation of plastic products (e.g., clothing, car tires, and building materials) during use. These tiny particles can be carried by wind to remote areas, expanding their spread and increasing the likelihood of entering the human body.

Beyond environmental persistence, mounting evidence points to direct risks to human health. Microplastics have been detected in various human tissues, with recent research indicating that even the brain accumulates these particles—at concentrations higher than those in the liver or kidneys [3]. Notably, this study found a significant increase in microplastic concentrations in liver and brain tissues from 2016 to 2024, and a strong association between elevated brain microplastics and diagnosed dementia, suggesting potential neurotoxic effects. Concurrently, studies on cellular impacts have demonstrated that microplastic exposure accelerates aging processes in fat cells, triggers inflammatory responses, and impairs adipogenesis [4]—further linking these pollutants to metabolic and systemic health disorders. Microplastics have been discovered in multiple human organs, including the carotid arteries, bone marrow, lungs, and uterus. The presence of microplastics in the carotid artery tissue increases the risk of heart disease, stroke, and death. All participants in a study had microplastics in their bone marrow, which may be a risk factor for blood tumors. In the lungs, microplastics were detected in healthy lung tissue samples adjacent to the lesions of most surgical patients [5]. And in the endometrium of infertile women, a variety of microplastics were found, with smaller particles more likely to enter the bloodstream and internal organs.

The sources of microplastics are diverse. On one hand, they come from the breakdown of large-scale plastic waste due to improper disposal. Global plastic production has skyrocketed from 2 million tons in 1950 to over 450 million tons in 2020, while the plastic recycling rate was extremely low (only 9% in 2019). Most plastics are landfilled or incinerated, and 22% are discarded in the environment, gradually breaking down into microplastics. On the other hand, there are direct sources such as plastic microbeads—added to some daily chemical products (e.g., facial scrubs, toothpaste, and shower gels) as abrasives. Each use washes these plastic particles into the water system. Synthetic fiber clothing also sheds more than 1,900 microfibers per wash, to enter these microplastics can easily pass through washing machine filters and urban sewage treatment systems

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to enter water bodies. Additionally, the friction of car tires against road surfaces generates rubber particles, which account for 28% of marine microplastic pollution and enter water and soil with rainfall.

Together, these studies underscore the multifaceted nature of the microplastic crisis: from environmental contamination across aquatic systems to insidious accumulation in human organs, and from known sources to previously unrecognized contributors like consumer products. Addressing this crisis requires a holistic understanding of microplastic distribution, exposure pathways, and biological impacts. This paper aims to synthesize current knowledge on the environmental occurrence, migration, and transformation of microplastics, clarify the multi-pathway human exposure mechanisms and their association mechanisms with major diseases (such as dementia, cardiovascular diseases, and reproductive disorders), quantify the ecological and health risks posed by microplastics from different sources (e.g., consumer products, plastic waste, and synthetic fibers), and further propose targeted, source-specific prevention, control, and governance strategies to provide a scientific basis for addressing the global microplastic crisis—building on the foundational insights provided by these and other key studies.

2. Method

The study selected three common types of microplastics as experimental subjects: low-density polyethylene (LDPE, commonly used in plastic bags), polypropylene (PP, widely used in food packaging boxes), and polyvinyl chloride (PVC, often used in pipe manufacturing). By adjusting the acidity of the water (pH 3–7), the amount of iron (1/10–1/50 of the plastic mass), and the amount of H2O2 (5–25 times the iron mass), the study systematically evaluated the degradation effects of the three Fenton-based methods under various conditions. The results indicated that Photo-Fenton was more effective for LDPE, while PP degradation proved challenging. This suggests that different plastics respond differently to the Fenton reaction due to their chemical structures and physical properties. The study not only explored the potential of Fenton methods in microplastic degradation but also provided a scientific basis for optimizing treatment processes, offering significant insights for the advancement of Microplastics pollution control technologies.

Figure 1 illustrates the mechanisms of Fenton and Photo-Fenton reactions. Blue and red in the figure denote the processes of the two reactions, respectively, with detailed depictions of how $Fe^{2+}$and H_2O_2 catalyze the generation of hydroxyl radicals in the Fenton reaction. Additionally, it highlights how UV light in the Photo-Fenton reaction enhances this process and boosts the reaction efficiency.

3. Result

The results were clear: PP was untreatable (no method broke it down). LDPE only reacted to Photo-Fenton (UV-C light helped weaken it). PVC was easiest—conventional Fenton and Photo-Fenton worked (Photo-Fenton performed better), but Fenton-like method did not. For LDPE/PVC, the best setup was acidic water (pH 3), enough iron (1/12 of LDPE mass, 1/10 of PVC mass), and tailored H_2O_2: a large amount (25x iron mass) for LDPE, moderate (11–15x iron mass) for PVC (too much H_2O_2 wastes radicals).

The results show that PP is difficult to degrade via Fenton-based methods. This can be explained from a materials science perspective: PP consists of long carbon-carbon single bonds, which are highly stable and resistant to attack by free radicals in the Fenton reaction. Also, PP polymer chains lack reactive functional groups, enhancing its degradation resistance. In contrast, LDPE is made of

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linear polyethylene molecules with more oxidation-sensitive sites, and PVC contains vulnerable chlorine atoms. Therefore, LDPE and PVC are more prone to oxidative degradation in the Fenton reaction.

The Conventional Fenton method leverages Fe^{2+} to catalyze H_2O_2 and generate hydroxyl radicals (•OH). Its reaction rate correlates closely with Fe^{2+} concentration, yet Fe^{2+} is prone to deactivation in alkaline or strongly oxidative settings. The Photo-Fenton method introduces UV-C light, which boosts the generation of •OH and enhances the degradation of specific microplastics, like LDPE. The Fenton-like method substitutes Fe^{2+} with iron powder. Under acidic conditions, iron powder is first oxidized to Fe^{2+}, after which the Fenton reaction is initiated. This gives the Fenton-like method unique advantages: in acidic or strongly reductive environments, iron powder is more stable and can continuously supply Fe^{2+}, thus avoiding the rapid deactivation issue that occurs with direct Fe^{2+} addition. Iron powder is also low-cost and easily accessible, making it suitable for large-scale applications. Additionally, the operation is simple—just controlling the acidic conditions can start the reaction, without the need for complex equipment or additional activation steps.

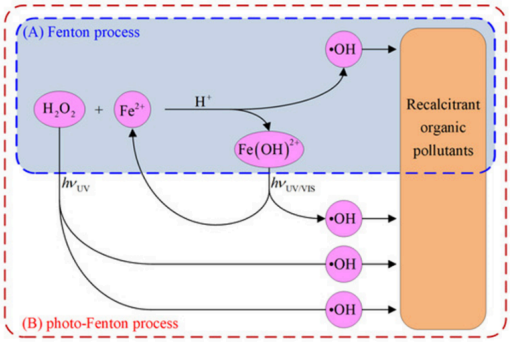

Figure 1. Schematic representation of (A) the Fenton process (outlined in blue) and (B) the Photo-Fenton Process (outlined in red) [6]

These methods don't fully remove LDPE/PVC in 60 minutes—they just "prep" them (loosen their structure, rough up their surface) to make bacteria breakdown easier later. the study concludes that Fenton-based methods help with LDPE/PVC (as a prep step) but not with PP; future work should test other tools (like UV + ozone) to cover all microplastics.

4. Conclusion

While Fenton-based methods shows potential in degrading LDPE and PVC microplastics, several factors need to be considered for its transition from the laboratory to practical applications, including its economic viability, safety, and sustainability. In terms of economic feasibility, the use of iron and hydrogen peroxide in the Fenton reaction must be carefully regulated to avoid unnecessary consumption and cost increases. It is also essential to consider the energy consumption of UV-C light in the Photo-Fenton method. From a safety perspective, the storage and transportation of iron powder and hydrogen peroxide must adhere to specific environmental conditions, such as keeping them dry and shaded, to prevent dampness, oxidation, or accidental reactions. Moreover, the strong oxidative hydroxyl radicals generated during the Fenton reaction must be strictly controlled to prevent safety hazards. In terms of technological improvements, further research can be done on combining Fenton-based methods with other technologies like UV and ozone to enhance degradation efficiency, especially for difficult-to-degrade microplastics like PP. Additionally, the development of novel catalysts, such as nanomaterials, can improve reaction rates and selectivity

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and optimize reaction conditions to reduce costs and energy consumption for the effective treatment of Microplastics pollution. Future research should further explore the feasibility of Fenton-based methods in practical applications to provide practical solutions for Microplastics pollution control.

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