How Heavy Metals Influence Microplastic Degradation: UV Absorption and Photoreactivity of PS-Fe_3O_4 Composites

Abstract:

Plastic pollution, particularly microplastics (MPs), presents a severe environmental risk due to the persistence, small size, and ability of plastics to coexist with harmful impurities. Of all MPs, polystyrene microplastics (PSMPs) are particularly noteworthy due to their large surface area, photoreactivity, and ability to last in the environment for long periods. This study investigates the role played by the interaction of heavy metals, especially iron oxide (Fe_3O_4), in the ultraviolet (UV) absorption and photoreactivity of PSMPs. Accordingly, the PSMPs' absorption coefficient was investigated using the UV–visible spectrometry under various concentrations and under the presence of Fe_3O_4. The findings showed that higher PSMP concentrations are typified by higher UV absorption, with the maximum occurring at 295 nm. Further, the presence of Fe_3O_4 enhanced the light absorption and thus indicates that various optical and surface characteristics can influence the pathways to degradation. The study emphasizes the possibility that heavy metals can alter the behavior of the MPs in the environment to influence photochemical stability and ecological implications. Finally, the study also uncovers more information about the mechanisms to degrade MPs and informs future research to tackle pollution control measures.

Introduction:

Plastic pollution is a rapidly growing global problem, attracting significant concern in all environment-related sciences. As one of the more concerning plastics, microplastics (MPs) refer to plastics with a particle size of < 5 mm. MPs are emerging contaminants with toxicity potential in humans (Manosuthi, 2024). Further, these plastics have extensive and significant effects on the environment, impacting ecosystems and wildlife (Silva et al., 2022). Microplastics' persistence, small size, and affinity to absorb toxic substances make these plastics a strange and concerning form of pollution. In addition, MPs have a high surface area and an active reaction at the surface, which can result in microplastics more easily being absorbed by a contaminant (e.g., heavy metals in water or air) (Bhattacharya & Khare, 2019).

Polystyrene microplastic (PSMP) is one type of microplastic. Due to its durability, mobility, and tendency to interact with pollutants, PSMP presents serious environmental challenges (Sarkar et al., 2021; Shiu et al., 2020). PSMP’s resistance to natural degradation means the microplastic can remain in ecosystems for long periods. With a low density that allows them to float, these particles are easily carried by wind and water currents across large distances (L. Wang et al., 2021; Weinstein et al., 2016). Polystyrene microplastics can absorb the sunlight in aquatic and terrestrial environments, influencing PSMPs degradation, thermal properties, and potential to leach toxic chemicals. To tackle such an issue, studying the absorption coefficient of PSMPs is essential (Astray et al., 2023).

The PSMP absorption coefficient is a quantitative measure of the efficiency with which PSMPs absorb light, especially in the ultraviolet (UV) spectrum, where polystyrene has strong absorption due to the presence of aromatic rings in the molecular structure of polystyrene (Hüffer et al., 2018; Hussein et al., 2020; Z. Wang et al., 2023). The numerical value of the absorption coefficient can depend on many factors, including the light wavelength, concentration, and particle size (Miskevich et al., 2019). Through understanding microplastic’s ability to absorb ultraviolet (UV) light, PSMPs’ photostability, the generation of toxic byproducts, and their role in modifying energy transfer and photosynthetic activity, which can influence the carbon cycle and aquatic organisms, can be determined (Luo et al., 2022). Furthermore, variations in absorption coefficients enable the understanding of the different optical properties of various microplastics, their identification, and their detection through spectroscopic methods. This information is required for monitoring pollution, understanding microplastic accumulation in the food chain, and estimating MPs’ further ecological and climatic impacts, such as the alteration of light scattering and heat transfer in aquatic ecosystems (Anton et al., 2021; Baho et al., 2021; Koestner et al., 2024). Lastly, research on the absorption coefficient has aided in the development of optical sensors for microplastic detection and informs the design of more sustainable and environmentally friendly materials, making this field of research fundamental in environmental science and materials engineering (Oh et al., 2021).

Studying the absorption coefficient of PSMPs when they interact with contaminants (e.g., heavy metals like iron) is also essential. The introduction of iron particles can influence the absorption coefficient of PSMPs by modifying their optical and physical properties (Adeleye et al., 2024;

Choi et al., 2025; Kim et al., 2024). Therefore, understanding these interactions is important for evaluating the environmental behavior of microplastics in the presence of metal particles. This understanding ultimately helps more accurately predict the photochemical degradation, light absorption, and ecological impacts of PSMPs.

In this study, we examine the absorption coefficients of PSMPs, both on their own and in the presence of heavy metals, specifically iron oxide (Fe_3O_4).

Methods and Materials:

2.1 Experimental Methods

Polystyrene microspheres with a size range of 4.8–5.8 μm and a density of 1.07 g/cc were obtained in powder form from Cospheric (Santa Barbara, CA). Black iron oxide (natural Fe_3O_4) was obtained from Amazon US (AC Alpha Chemicals, USA). Deionized (DI) water and a UV–visible (UV–Vis) spectrometer (Evolution 201) from Thermo Scientific, Inc. (Waltham, MA, USA) were used.

2.2. Sample Preparation

In this study, two sets of experiments were conducted.

Experiment 1: Preparation of PS Samples at Different Concentrations:

In this part, the samples were prepared using PSMPs in a concentration range of 0.05–1 g/L. Six samples were prepared by mixing 200 mg of PSMPs with DI water to achieve concentrations of 0.08 g/L, 0.5 g/L, 0.8 g/L, and 1 g/L. Then, the samples were sonicated for 20 minutes to ensure proper mixing of the solution.

Experiment 2: Preparation of the Mixture of PSMPs and Iron (Fe_3O_4):

For the preparation of the PS and Fe_3O_4 mixtures, three samples were prepared. The first sample contained PSMPs at a concentration of 1 g/L. The second sample consisted of a mixture of PSMPs and Fe_3O_4 in DI water, with the final concentration adjusted to 1 g/L. The third sample was a mixture of Fe_3O_4 and DI water, also at a concentration of 1 g/L. Then, all three samples were sonicated for 40 minutes.

2.3. UV–Vis-Spectrophotometer Analysis:

After being prepared, the samples were analyzed using UV–Vis spectroscopy over a wavelength range of 200–700 nm. A quartz cuvette with a width of 1 cm was used for the measurements.

After the analysis, the absorption coefficient of each sample was calculated using the Beer–Lambert law

$$\alpha = \frac{2.303 \times A}{l}$$

Where:

- α is the absorption coefficient
- **A** is the absorbance
- l is the path length

Results and Discussion:

In this research, we aimed to study the absorption coefficient of PSMPs in two scenarios: first at different concentrations and then under the influence of iron.

Impact of Concentration on Absorption Behavior:

According to Figure 1, minimal light absorption was observed at lower concentrations (0.08, and 0.1 g/L), with a maximum absorption peak around 295 nm. The absorption coefficient values for these concentrations remained relatively low. At 0.5 g/L, absorption increased while maintaining the maximum absorption wavelength at 295 nm. At even higher concentrations (0.8 and 1 g/L), absorption continued to rise, with the highest absorption coefficients measured at 295 nm (see Figure 2).

Intrinsic absorption coefficients are theoretically independent of concentration (Maes et al., 2018; Xia et al., 2018), but practical measurements of PSMPs are influenced by factors such as light scattering and particle agglomeration. At higher concentrations, deviations from the Beer–Lambert law were observed, likely due to particle interactions and aggregation as these can affect absorption behavior and lead to non-linear trends.

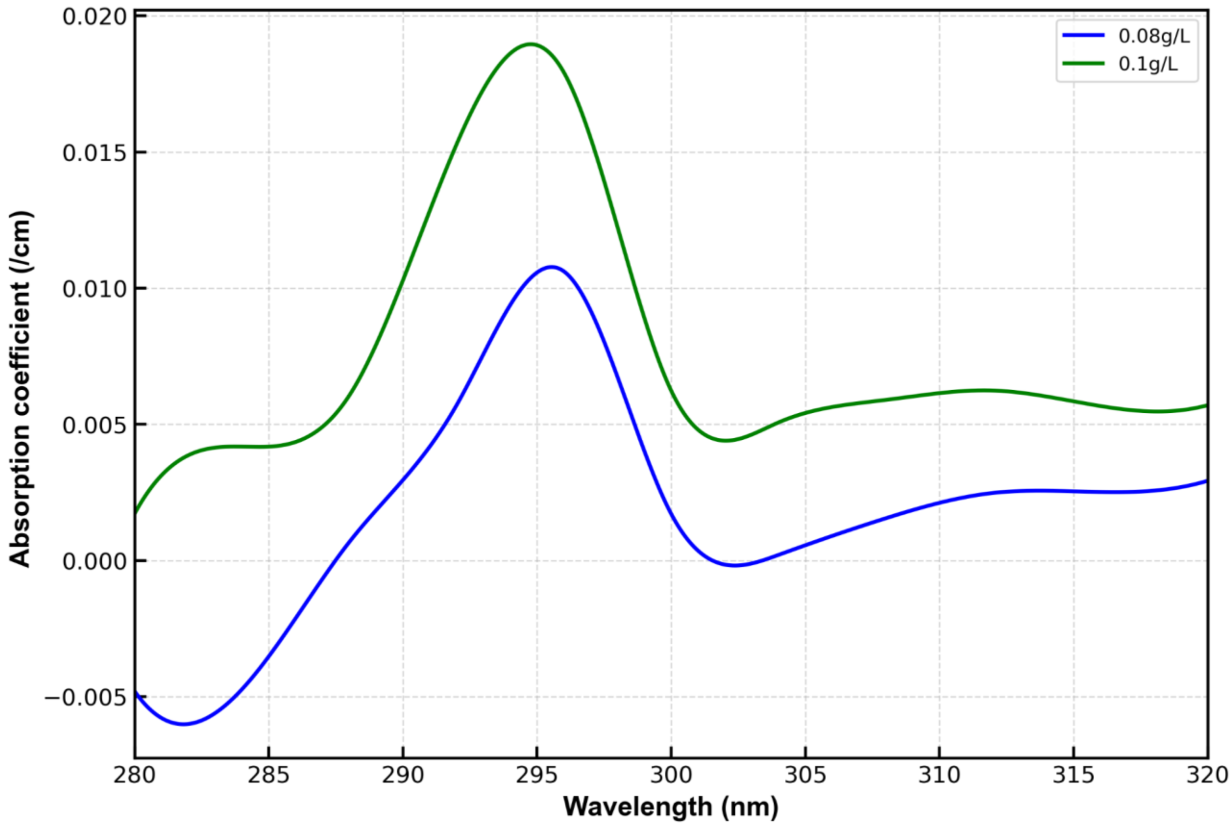

Figure 1: the relation between the adsorption coefficient and the wavelengths for different concentration of Polystyrene (PS) microplastic

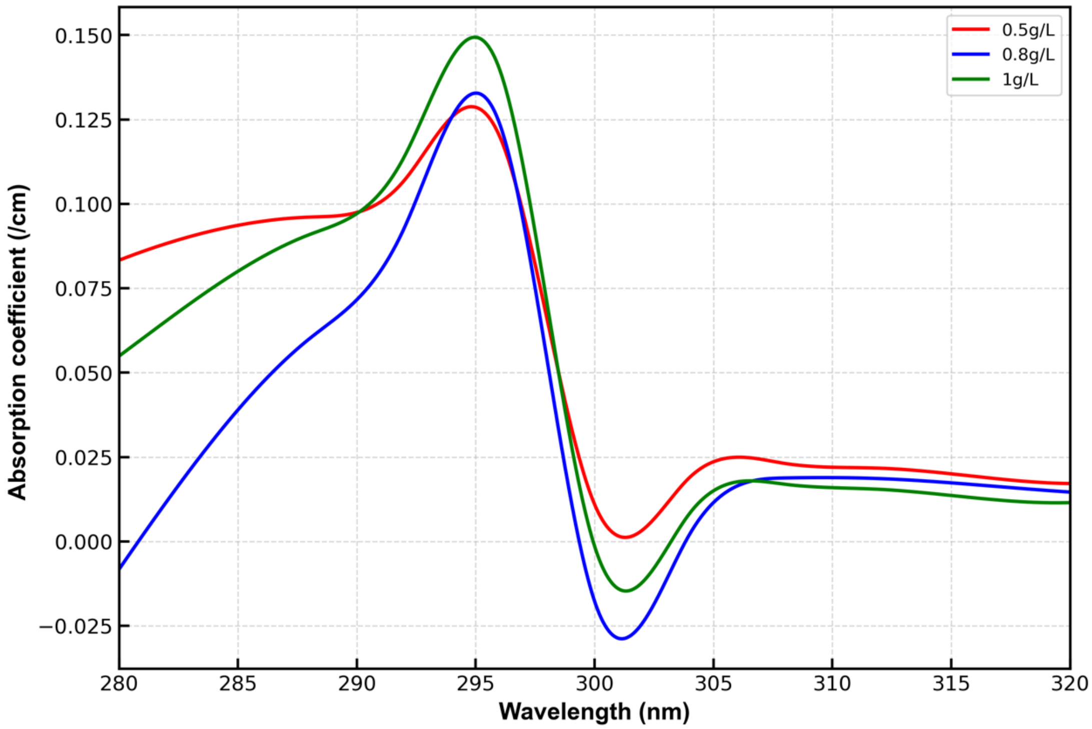

Figure 2: the relation between the adsorption coefficient and the wavelengths for different concentration of Polystyrene (PS) microplastic

Photochemical Influence of Iron:

In Figure 3, the absorption behavior of PSMPs mixed with Fe_3O_4 (PS+Fe_3O_4) is presented. The results indicate that the absorption of light by PSMPs increases when combined with Fe_3O_4. However, this absorption remains lower than that of pure Fe_3O_4, as shown by the blue curve in Figure 3. Notably, at 280 nm, the absorbance of the PS+Fe_3O_4 mixture exceeds that of both the individual PSMPs and Fe_3O_4 samples.

One interesting observation is the unexpected trend at 300 nm, where absorption initially increased but subsequently decreased. The introduction of iron particles into PSMPs significantly alters their interaction with light. Iron oxide, known for its strong light absorption—particularly in the UV and visible ranges—enhances the overall absorption capacity of the plastic-iron mixture (Lee et al., 2025; Rajapandi et al., 2025). This alteration occurs because iron does not merely remain embedded in the plastic but instead actively modifies its surface, influencing light scattering and reflection.

Under UV light, iron particles can trigger chemical reactions that degrade the plastic's structure, leading to the formation of new functional groups that absorb light more effectively. These new groups increase absorption at specific wavelengths and thus contribute to the observed variations. Additionally, the size, concentration, and distribution of iron particles play a crucial role in amplifying these effects. Our findings showed that smaller or well-dispersed iron particles enhanced absorption more effectively, highlighting the significant impact of iron on the optical behavior of microplastics when exposed to sunlight.

UV–Vis spectroscopy measurements confirmed that PSMPs have a strong absorption coefficient between 1–10 cm^{-1}, particularly at 295 nm. Further, introducing iron particles altered the absorption spectrum, with enhanced absorption. This behavior highlights how iron particles can accelerate UV-induced photodegradation of PSMPs, increasing the release of toxic byproducts.

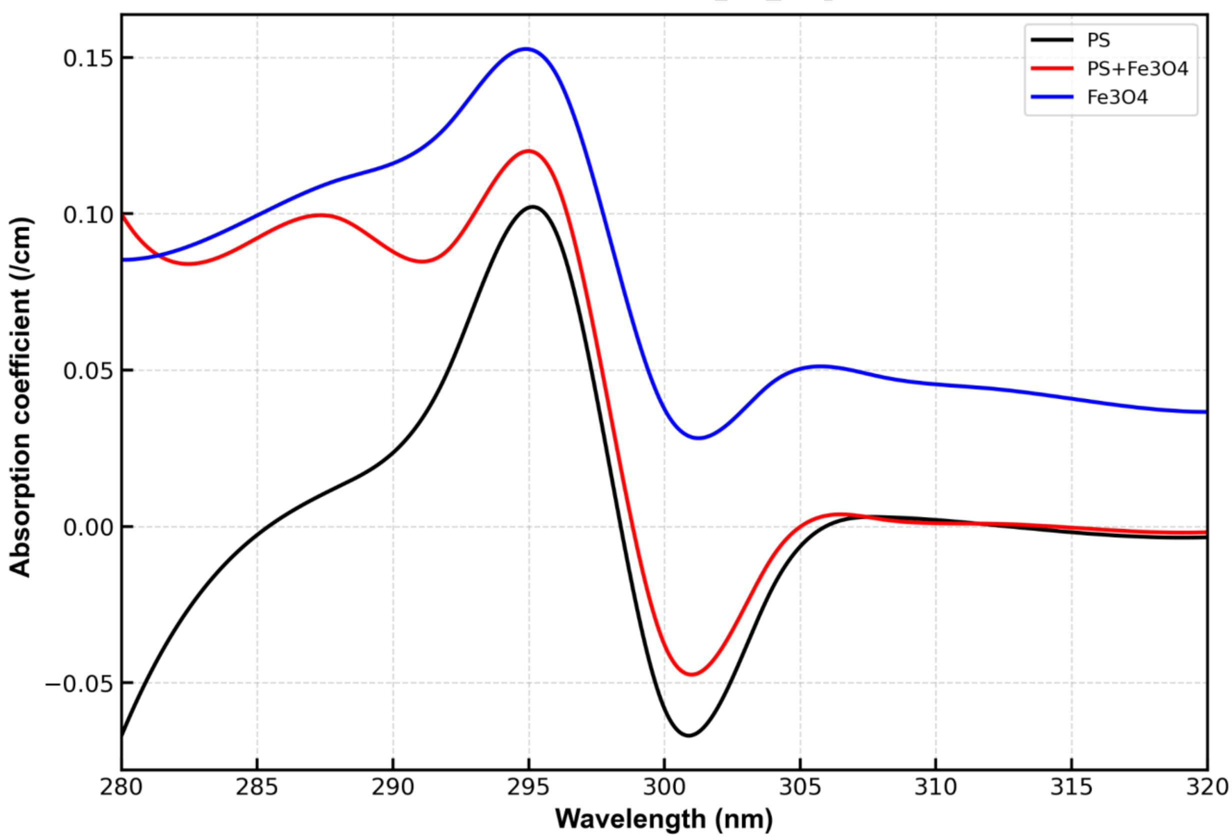

Figure 3: the competition between the adsorption coefficient of the Polystyrene (PS) microplastic, Fe3O4, and PS mixed with Fe3O4, and (PS+Fe3O4).

Conclusion:

To close the gap between experimental studies and environmental-impact assessments of microplastics, the measurement of the adsorption coefficient of MPs with heavy metals is critical. The parameter translates complex mechanisms of interaction into measurable parameters, which can be used to describe the behavior of the pollutant, ecological risk assessment, and regulations. The acquired knowledge from adsorption coefficient measurements must be used to establish pollution policy and protect human and ecological environments from the combined threats of microplastics and heavy metals. To better understand this critical ecological problem, future research should focus on improving adsorption models, studying the influence of biofilms, and testing adsorption behavior under realistic environmental conditions. Future research should also examine the absorption coefficient of other microplastics.

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Declaration:

During the preparation of this work the author used ChatGPT for editing, paraphrasing, and generating initial drafts. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

Conflict of interest:

On behalf of the author, the author states that there is no conflict of interest.

Data availability statement

The author confirms that the data supporting the findings of this study are available within the article.

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