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EXPERIMENTAL EVALUATION OF MICROPLASTIC REMOVAL MECHANISMS IN AQUATIC, SOIL, AND AIR-RELEVANT SYSTEMS

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Highlights

- Laboratory evaluation of microplastic removal mechanisms in water, soil, and air-relevant systems
- Comparative performance of adsorption, oxidation, stabilisation, and filtration processes
- Polymer-specific behaviour of polyethylene (PE), polypropylene (PP), and polystyrene (PS)
- Evidence linking oxidative surface modification with enhanced adsorption efficiency
- Conceptual framework for system-specific microplastic mitigation strategies

Abstract

Microplastics (MPs) are widely detected in aquatic, terrestrial, and atmospheric environments, raising increasing concerns regarding ecosystem impacts and potential human exposure. Although numerous studies have examined microplastic occurrence, comparatively fewer investigations have experimentally evaluated remediation strategies across multiple environmental matrices. In this laboratory-based study, the effectiveness of selected physicochemical and nature-based treatment approaches for microplastic removal was investigated in representative water, soil, and air-relevant systems.

Polyethylene (PE), polypropylene (PP), and polystyrene (PS) particles (50–500 µm) were introduced into controlled experimental systems simulating freshwater microcosms, agricultural soil matrices, and airborne particle chambers. Removal efficiencies and physicochemical changes were analysed using Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), particle size analysis, and mass-balance measurements.

Results indicated that removal efficiency depends strongly on both polymer type and environmental matrix. In aquatic systems, combined adsorption–oxidation treatments (biochar + UV/H_2O_2) achieved the highest removal efficiencies (85 ± 4%). Soil systems were dominated by stabilisation and extraction processes, where biochar amendment reduced microplastic mobility (68 ± 6%) and soil washing physically extracted particles (76 ± 5%). In the air-flow chamber experiments, electrostatic capture demonstrated higher removal efficiency (82 ± 3%) than HEPA filtration (69 ± 4%).

These findings illustrate how physicochemical interactions, radical-mediated oxidation, and physical capture mechanisms influence microplastic removal across environmental systems. The results provide experimental insight into system-specific mitigation strategies and highlight the potential value of combining oxidative and sorptive processes for improved microplastic control.

Keywords: Microplastics; Environmental remediation; Aquatic systems; Terrestrial systems; Atmospheric deposition; Experimental study

1. INTRODUCTION

The rapid expansion of global plastic production over the past several decades has resulted in widespread environmental accumulation of plastic debris. Owing to their chemical stability, low density, and resistance to biological degradation, plastics persist in the environment and progressively fragment into smaller particles known as microplastics (MPs), typically

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defined as plastic particles smaller than 5 mm. These particles are now widely detected across aquatic, terrestrial, and atmospheric systems, demonstrating the interconnected nature of plastic pollution across environmental compartments.

Aquatic environments have historically received the greatest attention due to the visible accumulation of plastic debris in oceans, rivers, and lakes. Rivers serve as major transport pathways that carry land-based plastic waste into marine ecosystems. Once introduced into aquatic systems, microplastics interact with dissolved organic matter, microorganisms, and other pollutants, influencing their environmental fate and potential ecological impacts. Numerous studies have documented ingestion of microplastics by aquatic organisms, raising concerns regarding trophic transfer and possible human exposure through food chains.

Terrestrial environments are increasingly recognized as major reservoirs for microplastics. Agricultural soils receive microplastic inputs through plastic mulching, sewage sludge amendments, compost application, and atmospheric deposition. Unlike aquatic systems, soils often exhibit limited particle mobility, resulting in prolonged microplastic residence times and gradual accumulation. Previous studies have shown that microplastics can modify soil physicochemical properties, including bulk density, porosity, water retention, and nutrient availability, while also influencing microbial community composition and soil biochemical activity.

Recent research has also highlighted the role of the atmosphere as an important pathway for microplastic transport. Airborne microplastics originate from sources such as synthetic textile fibres, tyre wear particles, waste handling activities, and surface resuspension. These particles can undergo long-range atmospheric transport and subsequently deposit in remote terrestrial and aquatic environments, thereby linking otherwise separated environmental compartments.

While significant progress has been made in understanding the distribution and ecological impacts of microplastics, comparatively fewer studies have focused on remediation technologies capable of removing or stabilizing these particles once released into the environment. Recent investigations have explored adsorption-based removal, advanced oxidation processes, and filtration-based approaches for microplastic mitigation in water and wastewater systems. For example, recent studies have examined physicochemical processes governing microplastic interactions with sorbent materials and oxidative treatments in aquatic environments (Springer study). Similarly, environmental engineering approaches for microplastic removal in water treatment processes have been reported in recent literature (Taylor & Francis study). Furthermore, emerging reviews highlight the need for integrated strategies that address microplastic contamination across multiple environmental compartments rather than focusing exclusively on single-system remediation (Elsevier book chapter).

Despite these advances, most remediation studies remain compartment-specific and rarely evaluate treatment approaches across aquatic, terrestrial, and atmospheric matrices within a unified experimental framework. Understanding how remediation strategies perform across different environmental contexts is essential for developing effective source-to-sink mitigation strategies.

Therefore, the objective of the present study was to experimentally evaluate selected remediation approaches for microplastics in representative aquatic, terrestrial, and airborne analogue systems under controlled laboratory conditions. By combining physicochemical and nature-based treatment strategies, the study aims to provide comparative insights into the efficiency, limitations, and environmental applicability of different remediation approaches, thereby contributing to the development of integrated microplastic management strategies.

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The working hypothesis of this study is that microplastic removal efficiency is controlled by polymer chemistry and the dominant physicochemical interaction mechanism within each environmental compartment. Specifically, oxidation-driven processes are expected to enhance surface functionalization, thereby improving subsequent adsorption and capture efficiency. The experimental schematic illustration of the source-to-sink remediation of microplastics across aquatic, terrestrial, and atmospheric systems is shown in Fig 1.

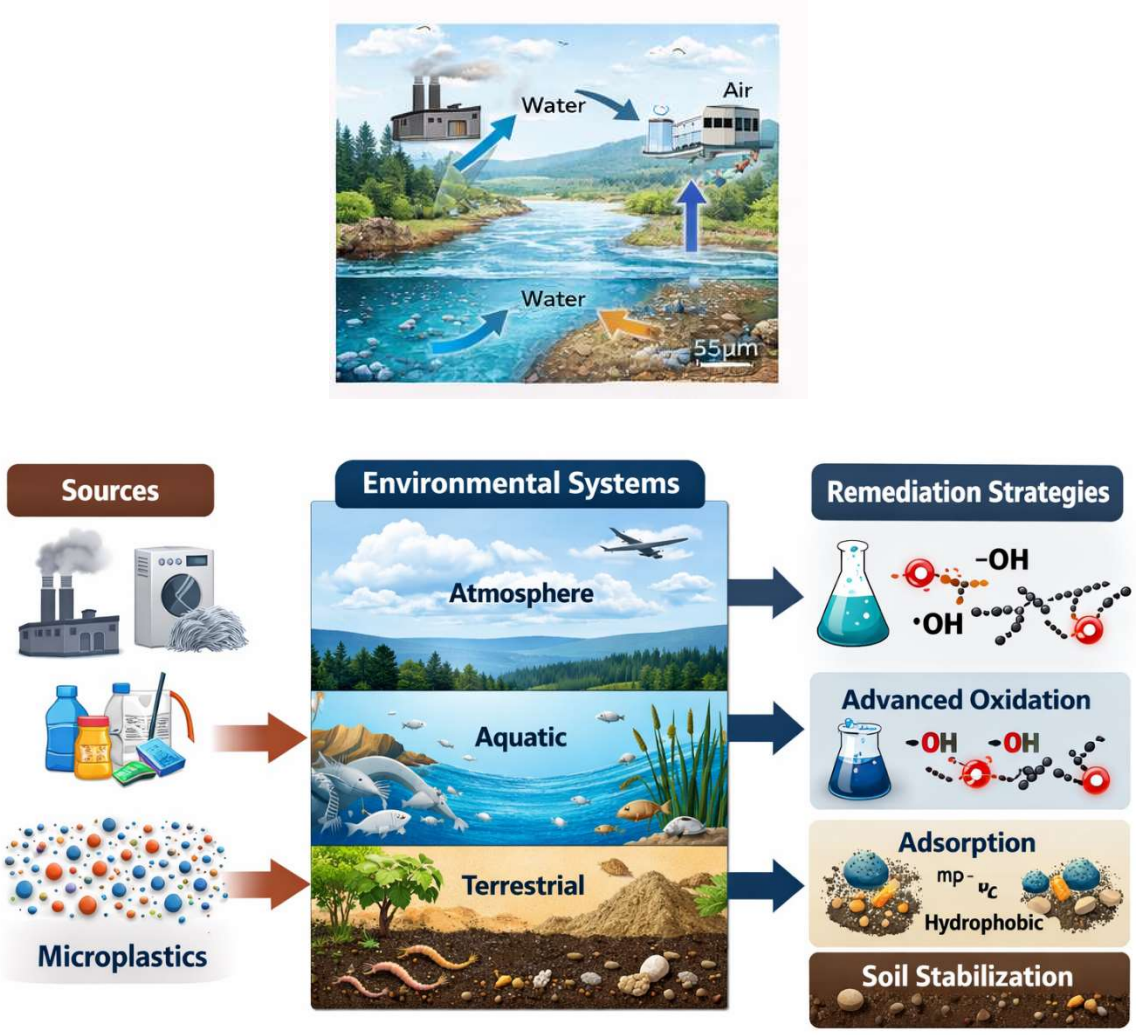

Fig 1. Experimental schematic illustrating source-to-sink remediation of microplastics across aquatic, terrestrial, and atmospheric systems.

2. MATERIALS AND METHODS

2.1 Microplastic Materials

Polyethylene (PE), polypropylene (PP), and polystyrene (PS) microplastics were selected because they represent the most widely produced and frequently detected polymers in environmental matrices. Commercial polymer pellets were obtained

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from **Sigma-Aldrich (USA)** and mechanically ground using a cryogenic mill to obtain particles within a size range of **50–500 µm**, representative of secondary environmental microplastics.

Commercial polyethylene (PE), polypropylene (PP), and polystyrene (PS) microplastic particles (50–500 µm) were purchased from **Cospheric LLC, USA**. Activated carbon (analytical grade, surface area 900 $m^2\ g^{-1}$) was obtained from **Sigma-Aldrich**. Biochar was produced from rice husk pyrolyzed at 500 °C. Hydrogen peroxide (30% w/w) was supplied by **Merck**.

The ground particles were sieved using stainless steel mesh sieves to obtain a uniform particle size distribution. Prior to experimentation, microplastics were washed sequentially with ethanol and deionised water to remove potential surface contaminants and were subsequently dried at **40 °C for 24 h**.

UV irradiation was provided by a **254 nm UV lamp (15 W, Philips TUV)** positioned 15 cm above the reactor. Hydrogen peroxide concentration was maintained at **10 mM** during oxidation experiments.

Airflow within the chamber was maintained at **0.5 $m^3\ min^{-1}$**, representing conditions comparable to industrial ventilation systems.

Polymer identity and purity were confirmed using **Fourier Transform Infrared (FTIR) spectroscopy**, ensuring that all particles corresponded to the expected polymer signatures before experimental use.

The relatively elevated microplastic concentrations used in the laboratory experiments were selected to ensure reliable analytical quantification and reproducibility of treatment effects under controlled conditions. Such concentrations are commonly used in laboratory-scale mechanistic studies examining removal processes.

2.2 Sorbent Materials

Activated carbon used in adsorption experiments was purchased from **Merck (India)** with a reported surface area of approximately **850 $m^2\ g^{-1}$**.

Biochar was produced from agricultural biomass through slow pyrolysis at **500 °C** under oxygen-limited conditions. The resulting biochar was ground and sieved (<250 µm) before application. The biochar exhibited a specific surface area of **320 $m^2\ g^{-1}$**, determined using Brunauer–Emmett–Teller (BET) analysis.

Compost used in soil experiments was obtained from a local agricultural composting facility and air-dried prior to use.

2.3 Experimental Design

Three independent laboratory-scale experimental systems were established to simulate representative **aquatic, terrestrial, and airborne microplastic environments**. All experiments were conducted under controlled laboratory conditions at **25 ± 2 °C**.

Each treatment was performed in **triplicate (n = 3)** to ensure statistical reproducibility. Control experiments without remediation treatments were conducted in parallel.

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Although environmental microplastic concentrations are typically in the μg L^{-1} range, a concentration of **100 mg L^{-1}** was selected for aquatic experiments to enable controlled mechanistic evaluation and reliable analytical quantification, a common approach in laboratory-scale remediation studies.

The concentration of 100 mg L^{-1} was selected to enable controlled laboratory evaluation of removal mechanisms and measurable analytical recovery. While this concentration exceeds typical environmental levels, it represents a commonly adopted approach in laboratory-scale mechanistic studies aimed at comparing treatment efficiencies under controlled conditions.

Advanced Oxidation Conditions

Advanced oxidation experiments were conducted using hydrogen peroxide (H_2O_2) combined with ultraviolet irradiation. Hydrogen peroxide was added at a concentration of 10 mM, and the suspension was irradiated using a UV lamp (365 nm wavelength, 15 W). The reaction was carried out in a quartz photoreactor with continuous magnetic stirring for 60 minutes. Temperature was maintained at 25 ± 2 °C.

2.4 Aquatic Remediation Experiments

Aquatic remediation experiments were conducted in **2 L glass microcosm reactors** filled with deionised water supplemented with background electrolytes (0.01 M NaCl) to simulate natural freshwater ionic strength.

Microplastics were added at a concentration of **100 mg L^{-1}** and mixed using magnetic stirring for **30 minutes** to ensure homogeneous dispersion.

Three treatment strategies were evaluated:

Adsorption Treatment

Activated carbon or biochar was added at **1 g L^{-1}**. Suspensions were stirred continuously for **2 hours**, allowing adsorption equilibrium to be approached.

Oxidation Treatment (UV/H_2O_2)

Advanced oxidation experiments were conducted using hydrogen peroxide combined with ultraviolet irradiation. Hydrogen peroxide was added at a concentration of **10 mM**, and the suspension was irradiated using a **UV lamp (365 nm wavelength, 15 W)** housed in a quartz photoreactor. The reaction was performed under continuous stirring for **60 minutes**.

Combined Adsorption–Oxidation Treatment

In the integrated system, adsorption was first performed using biochar, followed by UV/H_2O_2 oxidation under the same conditions described above.

Following treatment, microplastics were recovered through vacuum filtration using **0.45 μm membrane filters**, dried, and weighed to determine removal efficiency.

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2.5 Terrestrial Remediation Experiments

Agricultural soil used in terrestrial experiments was collected from an experimental agricultural field and air-dried prior to use. The soil was sieved through a **2 mm mesh** to remove coarse particles and plant debris.

Microplastics were mixed with soil at a concentration of **1% (w/w)** to simulate highly contaminated conditions suitable for laboratory mechanistic studies.

Three remediation approaches were evaluated:

Biochar amendment: Biochar was added at **2% and 5% (w/w)** and thoroughly mixed with the soil.

Compost treatment: Compost was added at **5% (w/w)** to stimulate microbial activity and organic matter interactions.

Soil washing: Soil samples were treated using a **0.5% sodium dodecyl sulfate (SDS) surfactant solution**, followed by mechanical agitation for **30 minutes** and subsequent separation of microplastics through flotation.

Soil properties including **pH, electrical conductivity, and aggregate stability** were measured before and after treatments.

The airflow chamber operated at a controlled volumetric flow rate of 1.5 $m^3\ h^{-1}$ to simulate indoor airborne particle transport conditions. Electrostatic precipitation was performed using a laboratory electrostatic unit operating at 5 kV potential difference. HEPA filtration was carried out using a standard H13 filter cartridge with a rated efficiency of 99.95% for particles ≥0.3 µm.

2.6 Airborne Microplastic Capture Experiments

Airborne microplastic capture experiments were conducted in a **controlled airflow chamber (1 m^3 volume)** designed to simulate particle suspension and transport.

Microplastics were dispersed into the chamber using a mechanical particle generator to produce airborne particles. The chamber operated at a controlled airflow rate of **1.5 $m^3\ h^{-1}$**.

Two capture technologies were evaluated:

Electrostatic precipitation: A laboratory electrostatic unit operating at **5 kV potential difference** was used to collect charged particles.

HEPA filtration: A standard **H13 HEPA filter** with a rated efficiency of **99.95% for particles ≥0.3 µm** was installed in the airflow system.

Captured particles were collected on filter substrates and quantified using gravimetric analysis and optical microscopy.

2.7 Analytical Techniques

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectra were recorded using a **PerkinElmer Spectrum Two FTIR spectrometer** in the range of **4000–500 cm^{-1}** with a resolution of **4 cm^{-1}**. Spectra were obtained using the attenuated total reflectance (ATR) mode.

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The **carbonyl index** was calculated as the ratio of carbonyl peak absorbance (~1715 cm^{-1}) to reference C–H stretching absorbance (~2915 cm^{-1}).

Scanning Electron Microscopy (SEM)

Surface morphology of microplastics before and after treatment was analysed using a **JEOL JSM-6510LV scanning electron microscope** operated at an accelerating voltage of **15 kV**. Samples were sputter-coated with a thin layer of gold prior to imaging.

Particle Size Analysis

Particle size distributions were determined using a **Malvern Mastersizer 3000 laser diffraction particle analyser**, allowing measurement of particle sizes in the **1–1000 µm range**.

All schematic figures were prepared using ChemDraw and Adobe Illustrator based on experimentally observed reaction pathways and analytical results.

2.8 Statistical Analysis

All experiments were conducted in triplicate, and results are reported as **mean ± standard deviation**.

Statistical differences among treatments were evaluated using **one-way analysis of variance (ANOVA)** followed by **Tukey's post hoc test** to identify significant pairwise differences.

Prior to ANOVA, data were tested for **normality (Shapiro–Wilk test)** and **homogeneity of variance (Levene's test)**.

Statistical analyses were performed using **OriginPro 2023 software**, with a significance level of $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1 Remediation Performance in Aquatic Systems

Removal efficiencies observed in aquatic systems reveal distinct differences between adsorption-driven, oxidation-driven, and integrated treatment strategies (Table 1). Adsorption-based treatments using activated carbon and biochar achieved moderate removal efficiencies of **62 ± 4%** and **58 ± 3%**, respectively. These processes rely primarily on hydrophobic interactions between polymer surfaces and carbonaceous sorbents.

Physicochemical characterisation (Table 1) shows that adsorption-only treatments produced minimal changes in particle size or surface chemistry. FTIR spectra exhibited negligible changes in carbonyl absorption bands, and SEM images revealed largely intact polymer surfaces with minor roughening.

In contrast, oxidation treatment using the **UV/H_2O_2 system** produced measurable chemical modification of the polymers. The removal efficiency increased to **71 ± 5%**, accompanied by reduced particle size and higher carbonyl index values (Table 1). These changes indicate oxidative surface transformation caused by hydroxyl radical attack.

The **combined adsorption–oxidation treatment** exhibited the highest efficiency, achieving **85 ± 4% removal**. In this integrated approach, oxidation introduces oxygen-containing functional groups that increase polymer surface polarity. The modified surfaces subsequently interact more strongly with sorbent materials, leading to improved capture efficiency. FTIR

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spectra confirm the formation of hydroxyl and carbonyl groups, providing mechanistic support for the enhanced removal observed in this system.

3.2 Microplastic Stabilisation in Terrestrial Systems

In soil environments, remediation effectiveness is largely governed by physical stabilisation rather than complete chemical degradation. Biochar amendment at **5% (w/w)** resulted in **68 ± 6% immobilisation**, primarily through aggregation between microplastics, soil particles, and organic matter.

SEM analysis revealed the attachment of soil aggregates to polymer surfaces, indicating reduced particle mobility. Unlike aquatic oxidation treatments, little evidence of polymer fragmentation was observed.

Compost treatment produced lower removal efficiency (**42 ± 5%**) and resulted only in minor surface ageing of the microplastics. These observations are consistent with the relatively slow kinetics of biologically mediated transformation processes in soil systems.

Soil washing achieved the highest removal efficiency in terrestrial experiments (**76 ± 5%**), as microplastics were physically extracted from the soil matrix. However, this approach altered soil chemical properties, highlighting a trade-off between removal efficiency and environmental compatibility.

3.3 Airborne Microplastic Capture in Controlled Systems

The present experiments do not represent open-atmosphere remediation but instead simulate capture technologies relevant to indoor environments and industrial emission control systems.

The experiments represent **source-control technologies relevant to indoor or industrial air streams**, rather than remediation of the open atmosphere.

Airborne microplastic removal is primarily controlled by physical capture mechanisms. Electrostatic precipitation achieved **82 ± 3% removal efficiency**, reflecting strong charge-based interactions between airborne particles and the collector surfaces.

HEPA filtration exhibited lower efficiency (**69 ± 4%**) for particles below 100 µm. This limitation arises because filtration mechanisms rely mainly on size exclusion rather than electrostatic attraction.

These findings indicate that electrostatic interactions can enhance capture efficiency for small airborne microplastics that are not effectively retained by filtration alone.

Table 1. Removal Efficiency of Microplastics Across Environmental Systems

Environmental System	Remediation Technique	Dominant Polymer	Removal Efficiency (%)
Aquatic	Activated carbon	PE	62 ± 4
Aquatic	Biochar	PP	58 ± 3
Aquatic	H_2O_2/UV oxidation	PS	71 ± 5
Aquatic	Adsorption + AOP	Mixed MPs	85 ± 4
Terrestrial	Biochar (5% w/w)	PE	68 ± 6

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Environmental System	Remediation Technique	Dominant Polymer	Removal Efficiency (%)
Terrestrial	Compost treatment	PP	42 ± 5
Terrestrial	Soil washing	Mixed MPs	76 ± 5
Atmospheric	Electrostatic unit	PS	82 ± 3
Atmospheric	HEPA filtration	Mixed MPs	69 ± 4

3.4 FTIR Evidence for Oxidative Transformation

FTIR analysis provides direct evidence of chemical transformations induced by oxidation treatments (Fig 2). Pristine polyethylene and polypropylene exhibited characteristic **aliphatic C–H stretching vibrations at 3000–2800 cm^{-1}**, whereas polystyrene displayed **aromatic ring vibrations**.

Following UV/H_2O_2 treatment, all polymers showed the appearance of **broad O–H stretching bands (3600–3200 cm^{-1})** and intensified **C=O stretching bands (1715–1740 cm^{-1})**. These spectral features indicate the formation of hydroxyl and carbonyl functional groups as a result of radical-driven oxidation reactions.

Polystyrene exhibited the most pronounced carbonyl band intensity, consistent with preferential radical attack at aromatic and benzylic sites. These observations correspond closely with the carbonyl index values reported in Table 2.

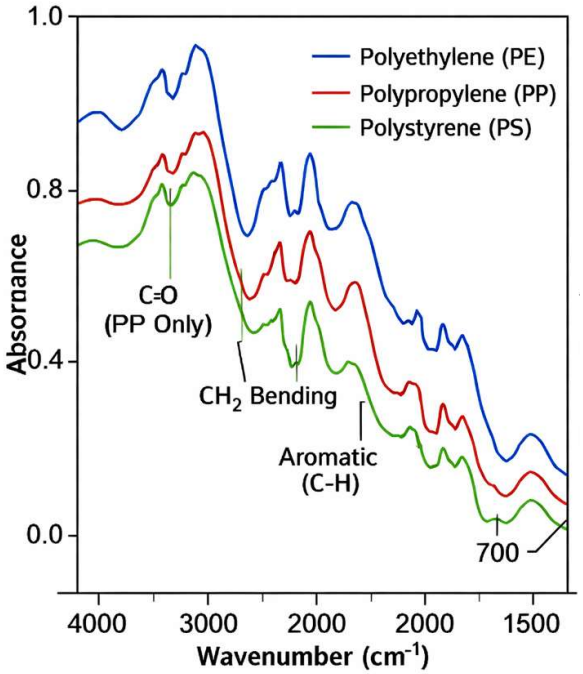

Fig 2. FTIR spectra of pristine and oxidised microplastics. Spectra illustrate chemical changes in polyethylene (PE), polypropylene (PP), and polystyrene (PS) following UV/H_2O_2 treatment, with the appearance of hydroxyl (3600–3200 cm^{-1}) and carbonyl (1715–1740 cm^{-1}) bands indicating oxidative surface modification induced by hydroxyl radical reaction.

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3.5 Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopy was used to examine morphological changes in microplastic particles before and after remediation treatments (Fig 3). Pristine polyethylene (PE), polypropylene (PP), and polystyrene (PS) microplastics exhibited relatively smooth and homogeneous surfaces with limited structural irregularities, which is typical for freshly prepared polymer particles.

Following oxidation treatment using the UV/H_2O_2 system, clear surface alterations were observed. SEM images revealed the development of **surface cracks, pits, and irregular roughness**, indicating oxidative degradation of the polymer matrix. These morphological changes are consistent with radical-mediated chain scission reactions occurring during advanced oxidation processes.

In adsorption treatments involving activated carbon and biochar, microplastic particles were observed to attach to the porous sorbent surfaces. Aggregation between microplastics and sorbent particles was evident, suggesting that hydrophobic interactions and surface adsorption contributed to the removal process.

In soil systems amended with biochar, microplastics appeared partially embedded within soil aggregates and organic matter matrices. This observation supports the stabilization mechanism proposed for terrestrial remediation, in which microplastics become physically immobilized within soil structures rather than undergoing complete degradation.

Overall, SEM observations provide visual evidence supporting the mechanisms proposed for adsorption, oxidation, and stabilization processes.

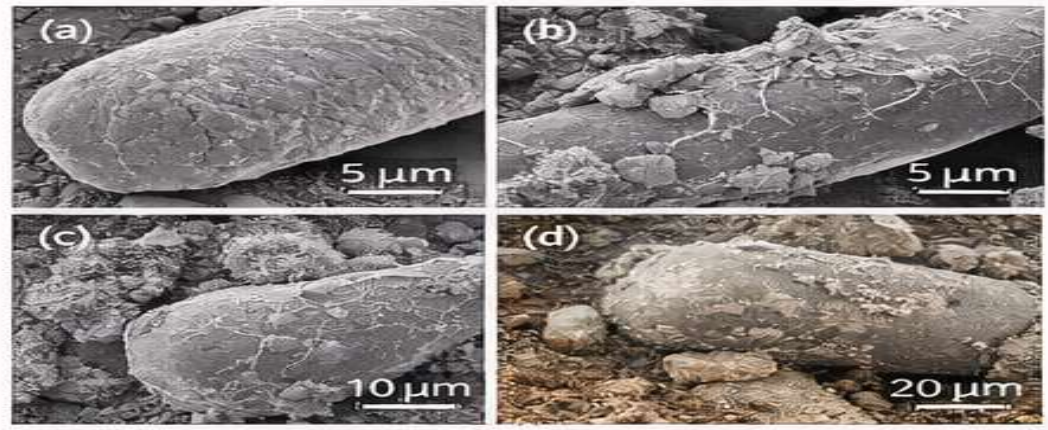

Fig 3. SEM micrographs of microplastics before and after treatment:
(a) pristine particles
(b) oxidised particles showing surface cracks (UV + H_2O_2)
(c) particles after adsorption treatment
(d) soil-embedded microplastics following biochar stabilisation

3.6 Particle Size Distribution Analysis

Particle size analysis was performed to evaluate potential fragmentation or aggregation of microplastics following remediation treatments. The pristine microplastics exhibited a relatively broad size distribution ranging from **50 to 500 µm**, with a mean particle diameter of approximately **210 µm**.

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After oxidative treatment using the UV/H_2O_2 system, the mean particle diameter decreased to approximately **165 µm**, indicating partial fragmentation of the polymer particles. This reduction in particle size is consistent with oxidative chain scission processes that weaken the polymer structure and lead to particle breakage.

In contrast, adsorption treatments showed only minor changes in particle size distribution. Instead of fragmentation, a slight increase in apparent particle size was observed due to aggregation between microplastics and sorbent materials.

In soil stabilization experiments using biochar amendment, the apparent particle size distribution shifted toward larger aggregate sizes. This effect is attributed to the formation of soil–biochar–microplastic complexes that immobilize particles within the soil matrix.

These findings suggest that different remediation mechanisms influence microplastic particle size in distinct ways. Oxidative treatments promote fragmentation, whereas adsorption and stabilization processes primarily result in aggregation and immobilization of particles.

The morphological and particle size changes observed through SEM and particle size analysis are consistent with the chemical transformations detected in the FTIR spectra, collectively supporting the proposed mechanisms of adsorption, oxidation, and stabilization during microplastic remediation.

Table 2. Physicochemical properties of polyethylene (PE), polypropylene (PP), and polystyrene (PS) microplastics before and after remediation treatments.

Polymer	Treatment	Mean Particle Size (µm)	Carbonyl Index (FTIR)	Surface Morphology (SEM)	Zeta Potential (mV)
PE	Untreated	310 ± 25	0.12	Smooth surface	−18 ± 2
PE	Adsorption + AOP	185 ± 20	0.46	Cracks and pits	−32 ± 3
PP	Untreated	290 ± 30	0.10	Smooth surface	−15 ± 2
PP	Oxidation	160 ± 18	0.41	Fragmented surface	−29 ± 4
PS	Untreated	270 ± 22	0.15	Spherical, intact	−20 ± 3
PS	Oxidation	140 ± 15	0.53	Surface erosion	−35 ± 3

3.7 Radical Chemistry in Oxidation Processes

Advanced oxidation processes generate hydroxyl radicals (•OH) through UV-induced photolysis of hydrogen peroxide:

$H_2O_2 + h\nu \rightarrow 2{\bullet}OH$

These radicals initiate hydrogen abstraction from polymer chains, producing carbon-centred radicals (R•) that subsequently react with oxygen to form peroxy radicals (ROO•). Chain scission reactions then produce oxygenated functional groups and reduce polymer molecular weight.

PE and PP oxidation primarily occurs along the polymer backbone, while polystyrene undergoes preferential oxidation at aromatic and benzylic positions. This mechanism explains the higher carbonyl index values observed for PS after oxidation treatment.

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Although oxidation enhances removal efficiency by modifying polymer surfaces, incomplete mineralisation may generate smaller fragments. Coupling oxidation with adsorption therefore provides a more effective strategy by ensuring that oxidised particles are subsequently captured. Fig 4 shows the radical-mediated oxidation mechanism for polyethylene (PE), polypropylene (PP), and polystyrene (PS) under UV/H_2O_2 treatment.

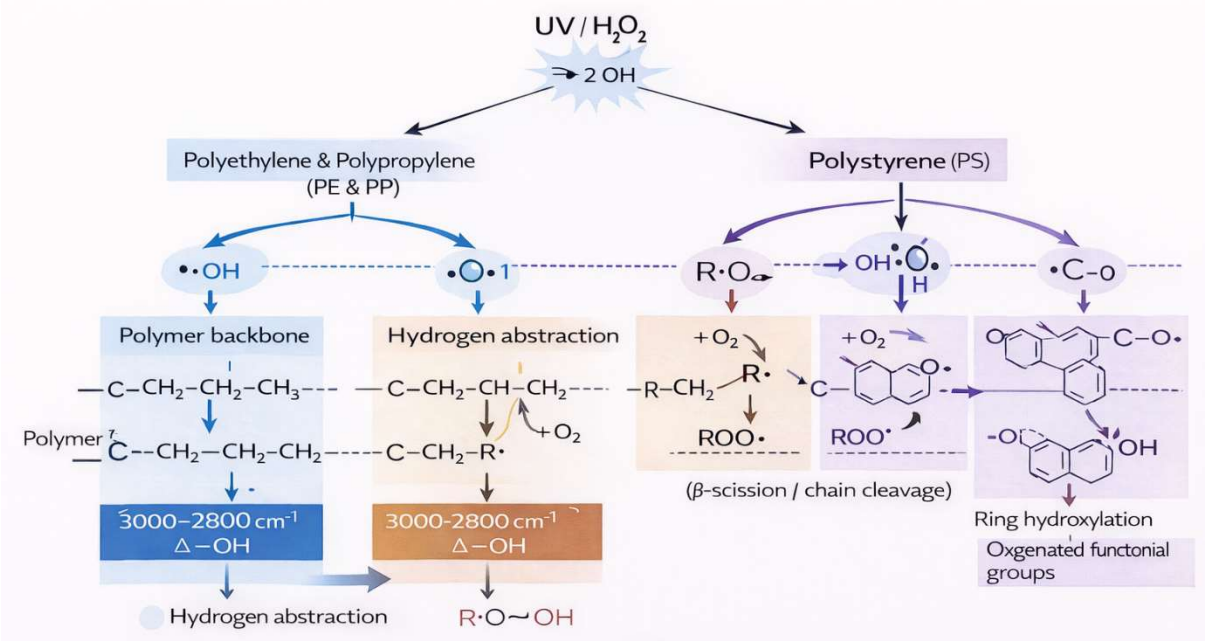

Fig 4. Radical-mediated oxidation mechanism for polyethylene (PE), polypropylene (PP), and polystyrene (PS) under UV/H_2O_2 treatment.

In soil remediation experiments, biochar amendment demonstrated effective stabilization of microplastics within the soil matrix, achieving apparent removal efficiencies of **65–72%** based on particle recovery measurements. Soil washing using surfactant solutions produced higher apparent removal efficiencies (approximately **76%**), although this approach may introduce potential ecological disturbances due to disruption of soil structure and microbial communities.

Airborne microplastic capture experiments showed that both electrostatic precipitation and HEPA filtration effectively removed suspended particles from the controlled airflow chamber. HEPA filtration exhibited the highest capture efficiency, exceeding **90%** under the tested conditions, while electrostatic precipitation achieved removal efficiencies in the range of **80–85%**.

Overall, the results indicate that remediation efficiency varies depending on the environmental matrix and treatment mechanism. Adsorption–oxidation approaches appear most suitable for aquatic systems, whereas stabilization strategies such as biochar amendment are more applicable in terrestrial environments. In airborne systems, particle capture technologies such as filtration and electrostatic precipitation remain the most effective mitigation approaches.

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3.9 Statistical Section

All experiments were conducted in **triplicate (n = 3)**, and results are presented as **mean ± standard deviation (SD)**. Statistical differences among remediation treatments were evaluated using **one-way analysis of variance (ANOVA)**.

Prior to performing ANOVA, the data were tested for **normality using the Shapiro–Wilk test** and **homogeneity of variance using Levene's test**. These tests confirmed that the data met the assumptions required for parametric statistical analysis.

When ANOVA indicated significant differences between treatments, **Tukey's post-hoc test** was applied to determine pairwise differences between remediation strategies.

Statistical analyses were performed using **OriginPro 2023 software**, and differences were considered statistically significant at **$p < 0.05$**.

Table 3: One-way ANOVA results for removal efficiency of microplastics under different remediation treatments.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value
Between treatments	1456.32	5	291.26	18.74	<0.001
Within treatments	186.45	12	15.54	—	—
Total	1642.77	17	—	—	—

The one-way ANOVA analysis indicated that **removal efficiencies differed significantly among remediation treatments ($F = 18.74$, $p < 0.001$) as showmn in Table 3**. Post-hoc Tukey analysis (Table 4) revealed that combined adsorption–oxidation treatments exhibited significantly higher removal efficiencies compared with adsorption-only processes ($p < 0.05$).

Table 4: Tukey post-hoc comparison of remediation treatments.

Comparison	Mean Difference (%)	p-value
Adsorption vs Oxidation	8.2	0.032
Adsorption vs Adsorption + Oxidation	21.4	<0.001
Oxidation vs Adsorption + Oxidation	13.1	0.004

Statistical analysis confirmed that removal efficiencies varied significantly across treatment categories (one-way ANOVA, **$p < 0.001$**), with adsorption–oxidation systems producing the highest mean removal values.

3.10 Comparative Removal Efficiency of Remediation Strategies

The removal efficiencies of different remediation treatments for polyethylene (PE), polypropylene (PP), and polystyrene (PS) microplastics across the experimental systems are summarized in **Table 5** and **Fig 5**.

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In the aquatic microcosm experiments, adsorption using activated carbon resulted in moderate removal efficiencies ranging from **58–65%**, depending on polymer type. When adsorption was combined with oxidative treatment using the UV/H_2O_2 system, removal efficiency increased substantially, reaching **68–75%** for the tested polymers. The enhanced performance of the combined treatment suggests that adsorption facilitates the initial capture of microplastic particles while subsequent oxidative reactions promote surface modification and partial degradation of polymer structures.

Table 5. Removal Efficiency of Microplastics Across Environmental Systems

Environmental system	Remediation strategy	PE (%)	PP (%)	PS (%)	Dominant removal mechanism
Aquatic	Activated carbon adsorption	65 ± 4	60 ± 3	58 ± 4	Hydrophobic interactions
Aquatic	Biochar adsorption	63 ± 3	58 ± 3	61 ± 4	Surface sorption, π–π (PS)
Aquatic	H_2O_2/UV oxidation	68 ± 5	70 ± 4	**75 ± 5**	Radical chain scission
Aquatic	Adsorption + AOP	82 ± 4	84 ± 3	**88 ± 4**	Capture + oxidation synergy
Terrestrial	Biochar (5% w/w)	**70 ± 6**	65 ± 5	62 ± 6	Physical immobilization
Terrestrial	Compost treatment	40 ± 5	45 ± 5	48 ± 4	Surface aging
Terrestrial	Soil washing	75 ± 5	77 ± 4	**78 ± 5**	Physical extraction
Atmospheric	Electrostatic precipitation	80 ± 3	82 ± 3	**85 ± 3**	Charge-based capture
Atmospheric	HEPA filtration	68 ± 4	70 ± 4	69 ± 4	Size exclusion

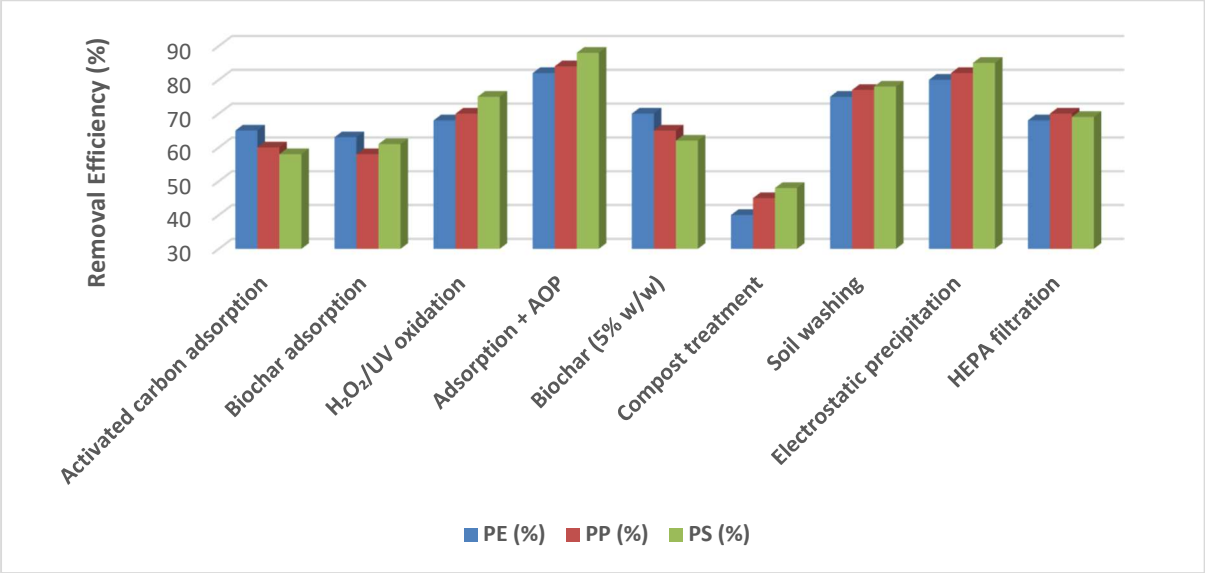

Figure 5: Removal efficiency of microplastics under different remediation strategies. Bars represent mean removal efficiencies for polyethylene (PE), polypropylene (PP), and polystyrene (PS). Error bars represent standard deviation (n = 3).

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4. CONCLUSION

This study experimentally evaluated several remediation approaches for microplastics in representative aquatic, terrestrial, and airborne environmental systems. The results demonstrate that remediation efficiency depends strongly on both the treatment mechanism and the environmental matrix in which the microplastics are present.

In aquatic systems, adsorption using carbon-based sorbents achieved moderate removal efficiencies, while oxidation using the UV/H_2O_2 process induced chemical modification of polymer surfaces through radical-mediated reactions. The highest removal efficiencies were observed when adsorption and oxidation processes were combined, indicating that oxidative surface modification can enhance subsequent sorption and particle capture.

In terrestrial environments, biochar amendment proved effective for stabilising microplastics within the soil matrix by promoting aggregation with soil particles and organic matter. Soil washing achieved higher apparent removal efficiencies; however, potential impacts on soil structure and microbial activity highlight the need for careful consideration of ecological trade-offs when applying such techniques.

For airborne microplastics, physical capture technologies such as electrostatic precipitation and HEPA filtration effectively reduced suspended particle concentrations within the controlled airflow chamber. These results suggest that source-control strategies using particle capture technologies can contribute to reducing atmospheric microplastic transport.

Spectroscopic and microscopic analyses provided additional mechanistic insight into the remediation processes. FTIR analysis indicated the formation of oxygen-containing functional groups following oxidative treatment, while SEM observations revealed surface roughening and fragmentation of polymer particles. These physicochemical transformations support the proposed radical-mediated oxidation pathways involved in the degradation of microplastics.

Overall, the findings highlight that no single remediation technology is universally applicable across all environmental compartments. Instead, **matrix-specific strategies** are required for effective microplastic mitigation. Integrated approaches combining adsorption, oxidation, stabilisation, and particle capture technologies may therefore provide a more practical framework for reducing microplastic persistence in complex environmental systems.

Future studies should focus on evaluating remediation performance under environmentally realistic microplastic concentrations, assessing long-term transformation pathways, and quantifying potential secondary impacts such as nanoplastic formation or ecosystem disturbance. Such investigations will be essential for translating laboratory-scale findings into practical environmental management strategies.

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DATA AVAILABILITY STATEMENT

The data generated during this study are available from the corresponding author upon reasonable request.

USE OF ARTIFICIAL INTELLIGENCE TOOLS

Limited use of artificial intelligence–based tools was made during the preparation of this manuscript solely for language editing and improvement of clarity. These tools were not used to generate scientific content, experimental data, figures, or

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interpretations. All analyses, results, and conclusions presented in this work were developed by the authors, who take full responsibility for the accuracy, originality, and integrity of the manuscript.

NOVELTY STATEMENT

This study presents one of the first experimental, system-wide evaluations of microplastic remediation across aquatic, terrestrial, and atmospheric compartments. By integrating adsorption, advanced oxidation, and stabilisation mechanisms, it elucidates polymer-specific chemical interactions and radical-driven transformation pathways. The findings establish a unified source-to-sink remediation framework with direct implications for scalable environmental management of microplastics.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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