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The role of biochar in combating microplastic pollution: a bibliometric analysis in environmental contexts

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Review

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Abstract

This study employs a bibliometric analysis using CiteSpace to explore research trends on the impact of biochar on microplastics (MPs) in soil and water environments. In agricultural soils, MPs reduce crop yield, alter soil properties, and disrupt microbial diversity and nutrient cycling. Biochar, a stable and eco-friendly material, has demonstrated effectiveness in mitigating these effects by restoring soil chemistry, enhancing microbial diversity and improving crop productivity. Recent studies report that biochar increases crop yields by 30–81%, even under high MP contamination levels (up to five times that of biochar-modified bacteria). Additionally, biochar enhances Olsen-P availability by 46.6%, increases soil organic carbon in microaggregates by 35.7%, and reduces antibiotic resistance genes by promoting beneficial microbes such as *Subgroup 10*, *Bacillus*, and *Pseudomonas*. In aquatic systems, biochar serves as an efficient adsorbent, particularly for MPs larger than 10 µm, including polystyrene. Studies suggest that fixed-column models achieve superior removal efficiency (95.31% ± 5.26%) compared to batch systems (93.36% ± 4.92%). Specifically, for MPs ≥10 µm, fixed columns reach 99% efficiency, while magnetically modified biochar captures 96.2% of MPs as small as 1 µm. These efficiencies stem from biochar's integration of physical and chemical mechanisms that enhance MP retention, particularly for MPs smaller than 10 µm, positioning it as a promising solution for nanoplastic remediation.

Introduction

Plastics are widely utilized in various industries and daily life due to their low production cost. The average global per capita consumption of plastic is 60 kg/year, with Europe exhibiting a significantly higher rate of 150 kg/year [1]. However, the rapid increase in plastic consumption is accompanied by the generation of substantial plastic waste. For example, China, the leading producer and consumer of plastic, generated 26.74 million tons of plastic waste in 2019, with projections indicating an increase to 34.82 million tons by 2035 [2]. Within Europe, Ireland has the highest per capita plastic packaging waste generation, approximately 67 kg/year [3]. Despite efforts to recycle plastic, only 9% of virgin plastic was recycled in 2015, with 12% incinerated and 79% accumulating in landfills or the natural environment [4].

Microplastics (MPs) have garnered significant attention due to their adverse impacts on human health and the ecological environment. Research primarily focuses on identifying their presence, risks, and sources in the environment and biota. Although MPs are produced in large quantities, effective removal techniques remain underdeveloped [5,6]. Recent studies have confirmed the widespread presence of MPs in agricultural soils and water bodies, highlighting their environmental and human health risks. In Yan'an, China, MP concentrations in agricultural soils reached 4505 ± 435 ng/kg, with polyethylene (PE) accounting for 37.4% of the total [7]. Similarly, in the United Kingdom, plastic-mulched soils contained 3680 ± 129.1 particles/kg, while non-mulched soils exhibited lower levels at 2667 ± 84.1 particles/kg [8]. The primary sources of MPs in agricultural soils include irrigation, fertilizers, farming practices (e.g., plastic mulching), and atmospheric deposition [5,6]. Additionally, recreational soils have been reported to contain higher MP concentrations than agricultural soils, as observed in Indore City, India [9].

MP contamination extends to water bodies, where seasonal variations influence the distribution of MPs. In South African rivers such as Crocodile and Luvuvhu, MP concentrations in water were higher during the dry season (5.4 particles/L) than in the wet season (3.3–4.3 particles/L), while sediment contamination was more severe during the wet season, with contamination factors categorized as "very high" (15.6) in wet periods and "high" (4.9) in dry periods [10]. Similarly, effluent from wastewater treatment plants contained 192 particles/L for 2 μm MPs and 323 particles/L for 10 μm MPs, underscoring the role of treatment facilities as pathways for MP release into aquatic environments [11].

The ecological and human health risks associated with MPs necessitate urgent mitigation strategies. In Yan'an, China, MP pollution loading indices ranged from 1.00 to 2.48, indicating light ecological pollution in agricultural soils [7]. In contrast, wastewater systems in Oman exhibited polymer indices ranging from moderate to extreme danger, emphasizing the need for enhanced MP removal technologies [12]. These findings highlight the pervasive nature of MP contamination across terrestrial and aquatic systems, reinforcing the importance of targeted remediation approaches.

To address MP contamination, various adsorbent materials have been investigated. Granular activated carbon at a concentration of 1.5 g/L has demonstrated adsorption efficiencies of up to 90% for MP fragments and fibers. Additionally, three-dimensional graphene oxide has shown adsorption capacities of up to 617.28 $mg \cdot g^{-1}$ for polystyrene MPs of 5 μm in size [13,14]. The integration of adsorbents with appropriate treatment models has further enhanced removal efficiency. For instance, coal gasification slag-based adsorbents combined with fluidized bed treatment achieved 99.2% MP removal, while granular activated carbon coupled with a fixed-column system attained 95.2% removal efficiency [15,16].

Biochar (BC) has emerged as a promising material for environmental remediation, offering benefits such as pollutant adsorption, soil improvement and climate mitigation. Life cycle assessments indicate that BC application can result in climate benefits ranging from −1.4 to −0.11 tonnes CO_2-eq per tonne of biochar [17]. Its versatility extends to removing pollutants, enhancing plant growth, and decolorizing organic dyes in wastewater [18-21]. Recent studies exploring the use of BC for MP remediation have yielded promising results, further emphasizing its potential for addressing environmental contamination.

Recent evaluations of MP removal methods have classified biological, physicochemical, and biochar-based techniques according to their treatment models, such as batch and fixed-column systems [22]. Modified biochars have been developed to enhance MP capture efficiency, including magnetic biochar, which facilitates easy separation from aqueous environments [22,23]. A comparative study by Mulindwa, et al. [24] assessed different biosorbents, including biochar, sponge/aerogel biomass-derived materials, and biomass-based graphene materials, revealing that biochar exhibits comparable efficiency to sponge/aerogel biomass-derived materials. Furthermore, while MP-induced soil alterations have shown positive responses in terms of enzyme activity [22,25], existing studies did not comprehensively assess MP removal efficiencies across different size ranges in aqueous environments, nor have they extensively evaluated the broader impact of MP contamination on soil ecosystems using BC. The role of modified BC functional groups in MP remediation also remains insufficiently explored. Moreover, bibliometric approaches have not been widely applied to visualize research trends in BC applications for MP mitigation.

To advance the understanding of MP pollution and biochar's remediation mechanisms, bibliometric analysis using Cite-

Space has proven instrumental. CiteSpace facilitates citation network visualization, co-citation analysis and the identification of emerging research trends, providing insights into the intellectual structure of this scientific domain [26]. By uncovering key contributors and trends, bibliometric tools support informed policy making and research prioritization. The application of bibliometric analysis enables an accessible and comprehensive visualization of research dynamics and development trends in BC-based MP remediation. Additionally, using authoritative journal databases such as “Social Sciences Citation Index” (SSCI), “Social Science Information” (SCI), and “Arts and Humanities Citation Index” (AHCI) ensures objectivity and scientific rigor, minimizing subjective biases and providing a broad perspective on research directions.

Thus, this study aims to (i) identify key research areas by analyzing topics, keywords, and relevant studies on “MPs and BC” through bibliometric methods, (ii) synthesize existing literature on major research themes, including modified biochar synthesis and its role in remediating contaminated environmental matrices, and (iii) expand the assessment of BC and modified BC in mitigating MP-contaminated soil by evaluating crop yield, microbial expression, gene activity, and enzymatic responses, while also analyzing the effectiveness of various modified biochars in removing MPs of different sizes in aqueous environments. The findings of this review provide critical insights into the current state and future directions of biochar's application in addressing MP pollution.

Review

Research methodology and analytical framework

Data collection and processing

The study employed bibliometric analysis using CiteSpace to examine publication trends and research topics related to MP removal with BC. CiteSpace was chosen for its ability to detect citation bursts and perform cluster labeling analysis, highlighting emerging research trends and intellectual structures. Compared to VOSviewer, which primarily visualizes co-authorship networks and keyword co-occurrences, CiteSpace provides advanced temporal and structural metrics, such as betweenness centrality, to map pivotal connections and identify transformative shifts in scientific literature. While VOSviewer excels in intuitive knowledge mapping over time, CiteSpace offers deeper insights into the dynamic evolution of research fields [27].

Bibliometric data were collected from the “Web of Science” (WOS) database to ensure comprehensive coverage and avoid the omission of relevant articles indexed in only one source. The data collection spanned January 2017 to December 2024, with the search process initiated at 02:59. Relevant keywords such as “microplastic” and “biochar”, along with their abbreviations, were used to capture a broad spectrum of literature. The dataset comprised 99 peer-reviewed journal articles, excluding conference papers, reviews, book chapters, editorials, errata, and comments to maintain credibility and research quality. Articles published before 2017 were excluded to focus on recent advancements and eliminate outdated or unreported studies. The procedure is illustrated in Figure 1.

Bibliometric analysis

The bibliometric analysis utilized citation and co-citation analysis to visualize knowledge structures and research trends. Quantitative techniques, including descriptive statistics, citation analysis, keyword clustering, and trend analysis, were applied to assess research impact and institutional collaborations. Higher citation frequencies indicated greater influence and stronger collaborative patterns. The trend analysis identified thematic clusters, research hotspots, and emerging frontiers, offering a comprehensive understanding of the field’s development.

In the knowledge mapping process, the node size represents the frequency of references or citations, while edge thickness reflects the strength of relationships between nodes [28]. The betweenness centrality of a node was defined using the Kleinberg burst detection algorithm, measuring the node’s influence within the network. The centrality value δs*ν was calculated as:

$$\delta_{s*}\left(v\right)=\sum_{t\in v}\delta_{st}\left(v\right)=\sum_{w:v\in P_x\left(w\right)}\frac{\sigma_{sv}}{\sigma_{sw}}\left(1+\delta_{s*}\left(w\right)\right). \qquad (1)$$

Nodes with high centrality values are indicative of key research topics and critical publications, distinguishing them as influential elements within the scientific domain. The intensity of hotspots is reflected in node frequency, while centrality values quantify a node’s relative importance [29].

Data filtering and quality control

To preserve analytical validity, articles irrelevant to the study’s scope were manually excluded based on their titles and abstracts. Exclusion criteria included retracted articles, those without full text or abstracts and studies lacking relevance to biochar (BC) or microplastics (MPs). The selected articles were systematically reviewed, categorized, and analyzed using bibliometric software. Data visualization facilitated the identification of research trends and relationships among publications, contributing to a clearer understanding of the field’s progression.

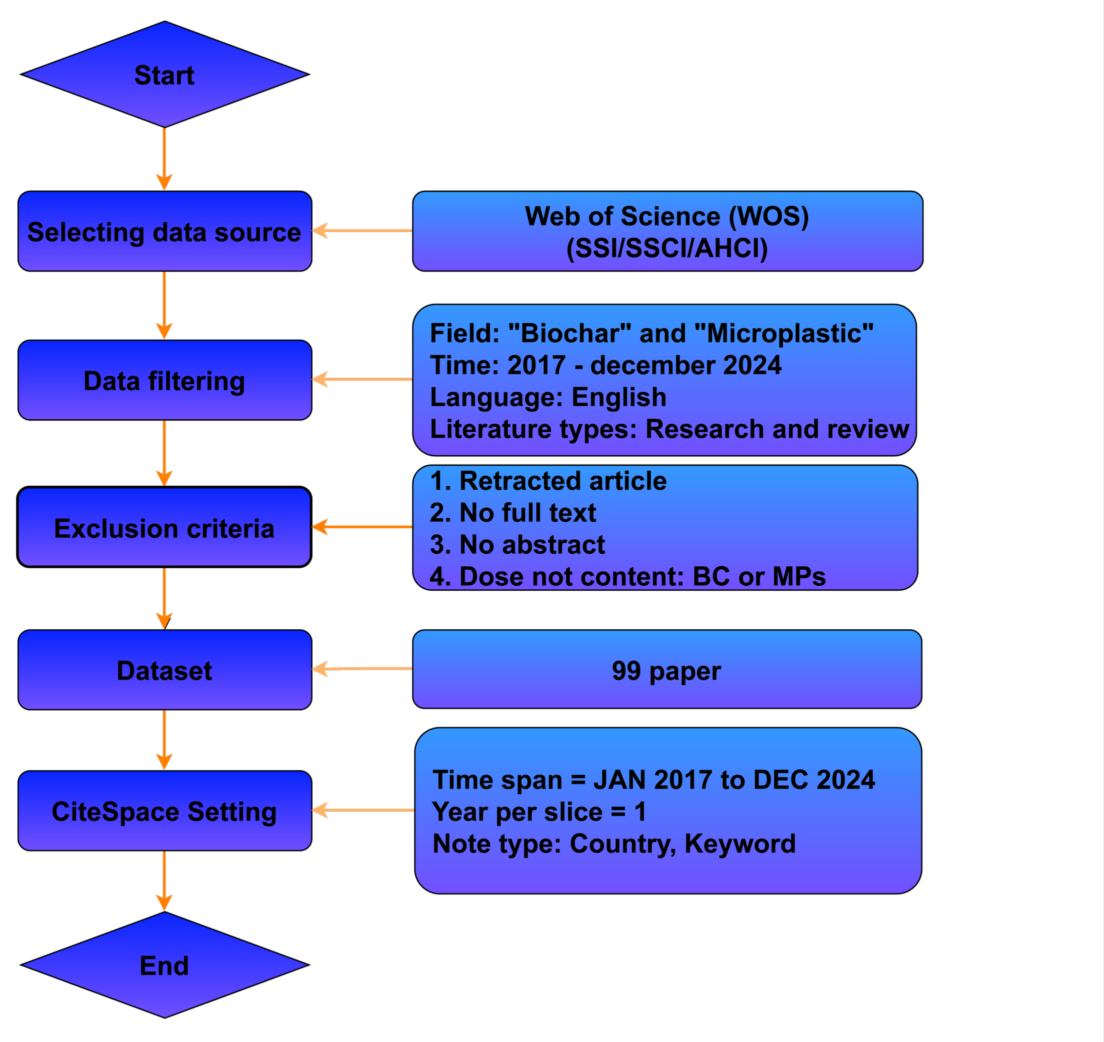

Figure 1: Data processing workflow and methodological processes.

Current status and thematic analysis

Bibliometric analysis

Publication trends: The annual number of publications and the geographical distribution of the authors publishing research on BC and MPs across the globe are illustrated in Figure 2. Research in this field began with one publication per year in 2017 and 2018, increasing to two publications in 2019, followed by four and five publications per year in 2020 and 2021, respectively. By 2024, the number of publications had surged to 41, a tenfold increase compared to 2020. This sharp growth underscores the rising interest of researchers and the scientific community in BC and MP as pressing and engaging research topics.

China is the leading contributor with 62 publications, followed by Canada, South Korea, and India. The significant research output from Asian countries highlights a growing regional focus on addressing the environmental and scientific challenges related to BC and microplastics MPs. As shown in Figure S1, Supporting Information File 1, four primary research themes have been explored at the national level since 2017, namely, (i) adsorption capacity and mechanisms, (ii) composting-related fertilizer applications, (iii) degradation of plastic mulch into polymers in soil, and (iv) pathways of plastic decomposition.

Trends and hotspot analysis: Using an AI-based bibliometric tool, a total of 99 publications were analyzed, resulting in the identification of 154 items grouped into nine primary keywords, that is, remediation, seed germination, co-pyrolysis, plastic mulch, community composition, MPs, rice biochar, enrichment, dissolved organic carbon, and modified biochar. As depicted in Figure 3a, the clustering and proximity of these items indicate frequent co-citation among the publications. Their temporal evolution is visualized in Figure 3b, while Figure 3c shows the frequency and connectivity of each keyword within the network. Among the top ten items with the highest centrality,

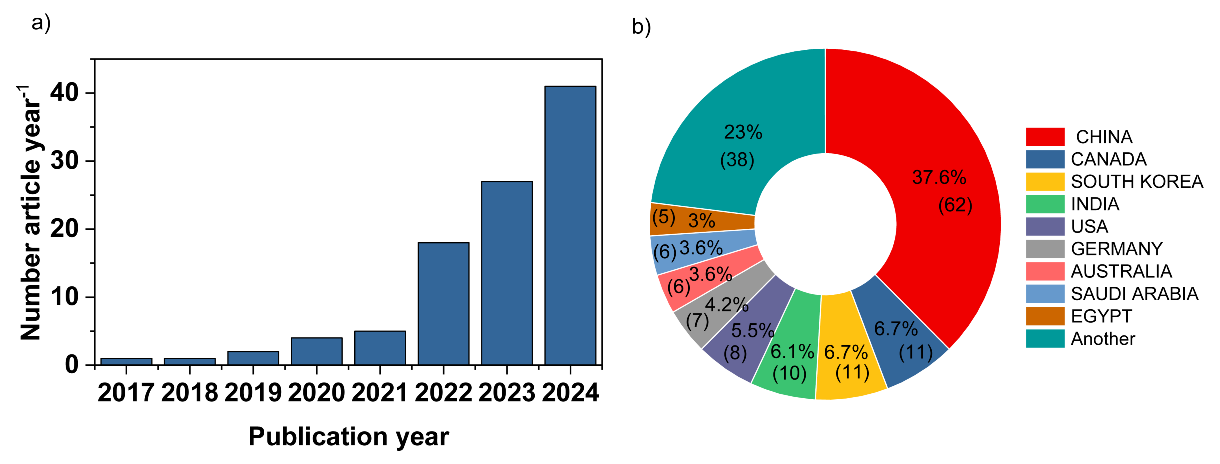

Figure 2: (a) Number of publications on BC and MPs per year and (b) top ten contributing nations worldwide.

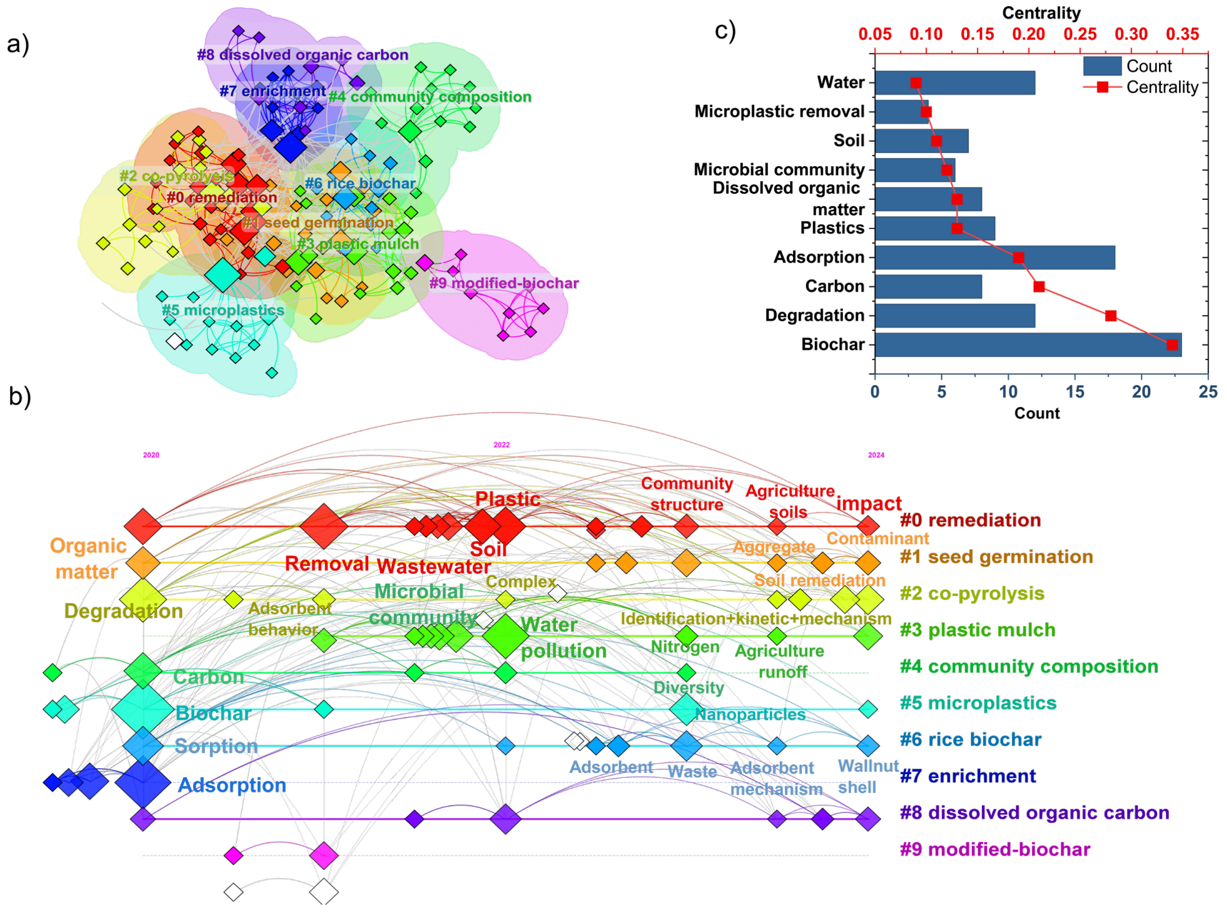

Figure 3: (a) Bibliometric network visualization of the published articles, (b) co-occurrence clustering map of keywords, and (c) chart illustrating centrality and count indices across 154 items.

“biochar” emerges as the core linking element across various research domains related to mitigating MP impact. The second most central item, “degradation”, has been a focal point since 2020, primarily examining the influence of MPs on soil organic matter and the role of biodegradable plastics, supported by biochar, in MP breakdown. Items such as “adsorption”, "plastic", "water", and "soil" (2021–2022) underscore the shift towards investigating MP adsorption in aquatic environments and its influence on microbial communities in soil.

Three clusters dominate the analysis, characterized by the highest frequency and centrality metrics, namely, "remediation," "plastic mulch," and "microplastic".

- Remediation: High-frequency keywords such as "soil", "wastewater", and "removal" dominated research from 2020 to 2022, reflecting efforts to mitigate MP pollution through biochar application in terrestrial and aquatic environments. From 2022 to 2024, terms like "community structure", "agriculture", and "impact" suggest a shift toward investigating biochar's influence on the physicochemical properties of soil and microbial community dynamics, particularly in agricultural systems.
- Plastic mulch: Keywords such as "microbial community" and "water" reflect studies (2020–2022) focusing on MPs derived from agricultural plastic mulch and their effects on microbial ecosystems and runoff. The research focus has since expanded (2022–2024) to encompass agricultural runoff assessments and urease enzyme activity in agricultural soils.
- Microplastics: "Biochar" remains the most central keyword, reinforcing its critical role in addressing MP contamination. From 2022 to 2024, the singular emergence of "nanoparticle" suggests a heightened research focus on biochar's ability to remove nanoscale MPs, given their significant risks to human health. However, detecting nanoplastics (NPs) in environmental matrices remains a challenge, necessitating advanced analytical techniques [30].

Additional keywords emerging from 2022 to 2024, such as "adsorbent", "adsorbent mechanism", "waste", and "walnut shell", highlight the development of biochar from agricultural residues and adsorption mechanism evaluations. Similarly, terms like "aggregate", "soil remediation", "identification", "mechanism", and "kinetics" indicate a research trajectory focused on optimizing modified biochar materials for MP mitigation.

Overall, biochar-based MP remediation has been investigated in two principal environmental matrices, that is, aqueous systems and soil, with an increasing emphasis on agricultural soils and runoff. Research efforts are intensifying towards nanoscale MP removal due to their hazardous implications. However, NP detection remains complex, requiring state-of-the-art methodologies [30]. For soil matrices, studies aim to enhance soil properties, enzyme activity and beneficial microbial communities, ultimately improving crop productivity. This underscores the necessity of interdisciplinary research integrating material science, agriculture, and microbiology in biochar–MP–plant interactions.

Three primary research trajectories emerge from the keyword analysis:

- Investigating how different biochar synthesis methods influence physicochemical properties, remediation efficiency, and environmental stability of MPs.
- Evaluating biochar's potential for MP remediation in agricultural soils, focusing on improvements in soil properties, crop yield, gene expression, and microbial communities.
- Examining biochar's adsorption mechanisms and MP removal efficiency in wastewater treatment applications.

Biochar synthesis techniques and functional optimization

Biochar synthesis

The synthesis methods for biochar, as illustrated in Figure 4, encompass traditional hydrolysis techniques and modified approaches utilizing materials such as magnetic modifiers, magnetic-derived amphoteric metals and cooperative microbes [31-34]. Traditional biochar synthesis aims to optimize specific surface area and structural stability by controlling reaction time, heating rate and reactor temperature [35].

For example, biochar produced from oilseed rape straw and softwood pellets at 700 °C exhibited a carbon distribution and surface area 3.45–6.15 times greater than that obtained at 550 °C [36]. Similarly, biochar derived from straw feedstock showed an increase in specific surface area (SSA) from 37.2 to 302.8 $m^2 \cdot g^{-1}$ when the pyrolysis temperature increased from 300 to 800 °C [37]. However, [38] reported contrasting trends in commercial corn straw biochar, where increasing thermolysis temperatures led to a significant decrease in surface area from 808.3 to 177.5 $m^2 \cdot g^{-1}$, while the bulk density increased from 0.059 to 0.121 $g \cdot cm^{-3}$. Similarly, biochar derived from hardwood using an open-fire stove exhibited a relatively low surface area of 292.8 $m^2 \cdot g^{-1}$.

Modified biochar synthesis strategies aim to enhance adsorption capacity while maintaining stable pore volume. For instance, magnetic biochar (MBC) synthesized from peanut shells using co-precipitation exhibited increases in SSA from 10.25 to 205.46 $m^2 \cdot g^{-1}$ and pore volume from 0.02 to 0.3 $cm^3 \cdot g^{-1}$ [39]. Studies on bamboo-derived biochar indicated that SSA and pore volume generally increased with py-

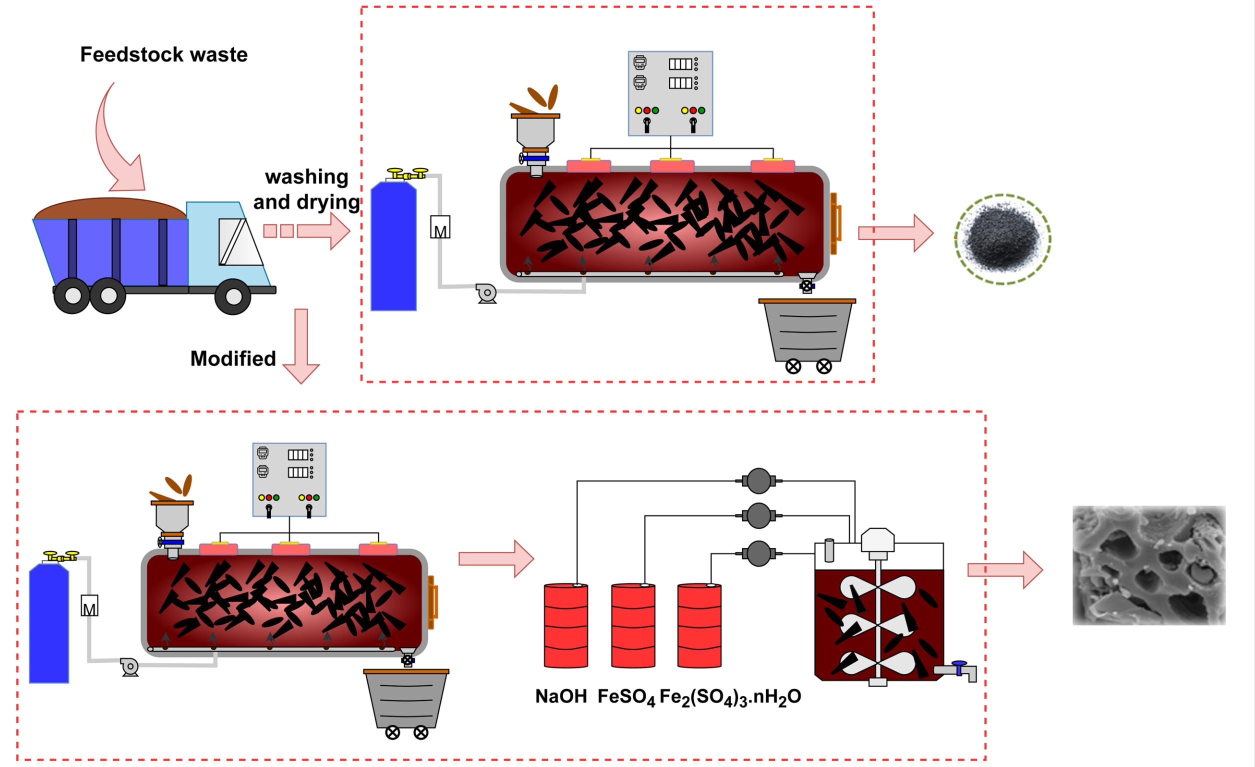

Figure 4: Production process of biochar and magnetic biochar.

rolysis temperature, although the pore volume decreases above 700 °C, suggesting 700 °C as an optimal temperature [40]. Functional modifications, such as those incorporating hydrophilic functional groups, improve biochar's ability to slowly release water molecules during dry cycles, reducing MP leaching risks and enhancing MP entrapment [41].

Temperature also affects functional groups in biochar. For example, enhanced diffusion, surface adsorption, and cation–π electron interactions were observed at 550 °C in *Polygonum amphibium L.* biochar. However, pyrolysis temperatures above 550 °C led to reduced stability [42]. Similarly, pyrolysis at 700 °C can increase SSA but may degrade oxygen-containing functional groups, affecting biochar stability [43].

The goal of modified biochar synthesis is to enhance its wastewater treatment and soil remediation capabilities by improving electrostatic and chemical bonding interactions with MPs, beyond the limitations of physical adsorption governed by specific surface area [44]. Magnetic biochar modification follows two main routes, that is, direct impregnation of feedstock or post-synthesis modification.

- Direct impregnation: Feedstock is washed and impregnated with 0.012 mol $Fe(NO_3)_3{\cdot}9H_2O$, stirred overnight, dried at 105 °C and heated at 550 °C for 2 h, yielding biochar with a surface area of 368.3 $m^2{\cdot}g^{-1}$ for sawdust [32].
- Post-synthesis modification: Pre-synthesized biochar is immersed in ferric and ferrous solutions at pH 10–11 for 24 h, resulting in Fe_3O_4 deposition on the biochar surface [45].

The incorporation of functional groups significantly enhances the efficiency of BC in MP removal. Specifically, MBC derived from sludge and red mud has demonstrated improved adsorption capacity for nanoplastics [43]. Furthermore, modifying feedstock with urea, ascorbic acid, and iron salts before pyrolysis enhances iron and nitrogen content, improving microbial community interactions in soil [31].

Biochar properties

The physical and chemical properties of biochar depend significantly on the composition of its feedstock [46]. Molecular model calculations and quantum chemistry analyses suggest that biochar derived from wood exhibits superior physical properties, such as porosity and surface area, compared to other materials [37].

Biochar produced from carbon-, oxygen- and nitrogen-rich straw at low pyrolysis temperatures retains a large number of functional groups, which enhance charge transfer potential and adsorption stability through increased surface charge density, charge distribution, and bonding orbital characteristics [37]. Feedstocks and preparation conditions for biochar are listed in Table S1, Supporting Information File 1. Biochar derived from palm kernel shells and coconut shells showed lower carbon content than the corresponding raw material [47]. The O/C ratio indicates the stability of biochar, while the H/C ratio reflects the presence of fused aromatic hydrocarbons [48]. Most biochar samples in Table S2 (Supporting Information File 1) exhibit an H/C ratio below 0.15, indicating high aromatic hydrocarbon content, and an O/C ratio below 0.6, demonstrating high stability, particularly for biochar derived from agricultural byproducts. Carbon and nitrogen content in biochar are critical for improving soil nutrients and microbial populations. Comparisons of biochar and urea application revealed significant increases in total nitrogen content in soil, that is, 0.32 g/kg for 3% biochar addition and 0.36 g/kg for 3% biochar combined with urea [49]. Biochar amendments consistently enhanced nitrogen content in both topsoil (0–20 cm) and subsoil (20–40 cm) compared to urea [50]. These favorable properties highlight biochar's potential for microplastic removal in water and its ability to restore functionality in microplastic-contaminated soils.

Biochar applications in restoring MP-contaminated soil

Improving plant growth under MP stress

MPs negatively impact crop performance by reducing biomass production, inhibiting stem and root development and consequently affecting fruit and seed formation [51]. This effect is primarily due to oxidative stress and cellular damage in plant roots, which diminishes water and nutrient absorption [52]. MPs disrupt root–soil hydrocarbon exchange pathways and hinder photosynthesis. Furthermore, they impair metabolic processes such as the tricarboxylic acid cycle and galactose metabolism [53]. For instance, high rubber-MP dosages (10% MPs) led to significant reductions in both shoot and root biomass in peanuts after 48 days of growth [52]. Similarly, adding 1% polypropylene (PP) to soil during chili cultivation reduced root biomass, shoot biomass, and plant height compared to controls without PP contamination [51]. The biomass of peanut roots and aboveground parts decreased by 28.45% and 16.45%, respectively, with 1.5% polystyrene (PS) contamination in the soil [53]. For sugarcane, polyethylene (PE) contamination resulted in biomass reductions of 4.2–8.6% for canes and leaves and 22.6–37.9% for roots, indicating that root systems are the most affected [54].

The potential of biochar in mitigating MP-induced stress and enhancing plant biomass is illustrated in Figure 5. Experiments with 0.5% cotton stalk biochar in polyvinyl chloride (PVC)-contaminated soils during wheat cultivation showed improved shoot and root biomass at a PVC concentration of 0.25%. However, at higher PVC levels (0.5%), root recovery was less pronounced [55]. Based on the compiled data in Figure 5a, biochar supplementation at 1.0–2.0% resulted in more than 39% biomass increase. Specifically, applying 1% biochar enhanced biomass by 63.47%, 51.24%, and 92.20% during the seeding, flowering and fruiting stages, respectively [51].

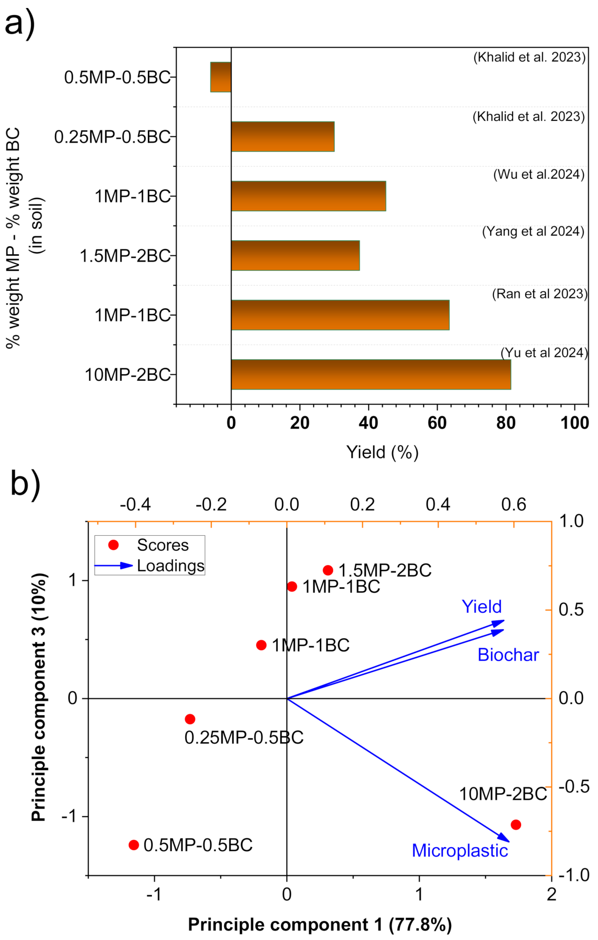

Figure 5: Plant biomass enhancement based on the percentage of MPs and BC in the soil (a) and PCA analysis based on yield, BC distribution and MPs (b).

Modified biochar, particularly when combined with beneficial microorganisms, exhibits even greater potential. For example, 1% corn stalk biochar-based microbial consortia (e.g., *Bacillus B28*) applied to soil containing 10% rubber crumb significantly increased peanut production by 58.86% and yield by 81.41% [52]. Principal component analysis (PCA) in Figure 5b reveals a strong correlation between biomass performance and biochar concentration, underscoring biochar's pivotal role in soil remediation and plant performance enhancement in MP-contaminated soils.

Enhancement of soil physicochemical properties

MPs exert significant impacts on soil physicochemical properties, altering its physical structure, chemical composition, and microbial community. Regarding soil physical properties, MPs modify porosity and aeration, which in turn disrupt water and air circulation, leading to soil compaction and dryness that adversely affect root development [52,54,56]. These changes are exemplified by the reduction in water-stable aggregates by approximately 20% and a decline in saturated hydraulic conductivity by up to 70%. Moreover, the water content in soil at field capacity decreases between 10% and 65%, depending on soil texture, MP concentration, and size distribution [56].

Biochar application has shown potential in mitigating these adverse effects. For instance, adding 1.5% apple tree branch biochar to soil maintains the stability of large macroaggregates (>5 mm) and increases the soil organic carbon content in microaggregates by 35.7%, thus promoting the formation of microaggregates within macroaggregates [57]. This illustrates the effectiveness of biochar in counteracting the physical degradation caused by MPs.

In terms of soil chemical properties, MPs influence pH, organic matter content, and macronutrient levels, including nitrogen (N), phosphorus (P) and potassium (K). For example, 3–7% low-density polyethylene (LDPE) MPs significantly reduce total exchangeable cations (Na^+, K^+, Mg^{2+}, and Ca^{2+}) by 4–6% [58]. Additionally, non-biodegradable MPs such as PE and PVC inhibit organic phosphate mineralization, alkaline phosphatase activity, and inorganic phosphate solubilization. By contrast, biodegradable MPs such as PLA do not affect alkaline phosphatase activity [59]. MPs also reduce available phosphorus (Olsen-P) levels by 9.7–38.6% (PE, PVC) and 38.4–73.6% polyactide (PLA) [60]. Furthermore, MPs compete with plant roots for phosphate adsorption, with distribution coefficients (K_d) in the order PVC (5.19 L/kg) > PE (4.23 L/kg) > PLA (2.48 L/kg) [60].

Biochar amendments can alleviate these chemical imbalances. For example, cotton and corn biochar added to soil contaminated with aged plastic mulch can increase Olsen-P levels by up to 46.6% during cotton cultivation [61]. These findings demonstrate the dual role of biochar in enhancing both physical and chemical properties of MP-contaminated soil, thereby improving overall soil functionality.

Enhancement of soil microbial communities

The restoration of soil nutrient cycling functions involves not only improving physicochemical properties but also addressing changes in biogeochemical cycles mediated by soil microbial communities. The effects of biochar on microbial diversity and activity in soils contaminated with MPs are summarized in Table S1, Supporting Information File 1. Biochar has demonstrated a capacity to enhance microbial diversity, as evidenced by multiple studies [51,53,54]. These improvements are most pronounced under well-watered conditions, although the effects on diversity may diminish or even reverse under dry or drought conditions [36].

Biochar also alters the composition of soil microbial communities exposed to MPs. Specifically, the abundance of microbial groups such as *Proteobacteria, Firmicutes, Patescibacteria* and *Cyanobacteria* decreases, while populations of *Actinobacteria, Chloroflexi, Acidobacteriota,* and chemoheterotrophs increase in the presence of MPs like PE, LDPE, and PS [53,62,63]. For instance, in wheat-cultivated soil exposed to PVC, biochar produced from cotton stalks at 650–750 °C increased microbial biomass nitrogen by 7–30% and microbial biomass carbon by 10–13%, enhancing the carbon and nitrogen cycling processes [55]. Similarly, the application of corn straw biochar in pepper-cultivated soil contaminated with PP elevated the abundance of *Acidobacteria and Bacteroidetes* by 1.32% and 1.37%, respectively [51]. Additionally, magnetic biochar restored fungal gene abundance in soils where PVC contamination (0.25% and 0.5%) had caused declines of 35.15% and 41.67%, respectively [55].

MPs are known to increase the abundance of antibiotic resistance genes (ARGs) in soil through adsorption, mobility, and propagation mechanisms [62]. MPs facilitate the movement and spread of ARGs by serving as carriers. For example, PS contamination at 1% increased ARG abundance to 0.26 copies per cell compared to 0.21 copies per cell in control soil [64]. MPs also promote the proliferation of multihost bacterial populations such as *Sphingomonas, Microvirga, Ilumatobacter, Skermanella,* and *Rubellimicrobium*, which harbor diverse ARGs. Increased populations of *Bacillus* and *Streptomyces* have also been associated with PS exposure [62,64]. Furthermore, the addition of fungicides to MP-contaminated soil has been linked to increased resistance genes for rifamycin, vancomycin, novobiocin, quinolone, and mupirocin [65]. However, studies have shown that coconut shell biochar can reduce ARGs, including sulfonamide and tetracycline resistance genes, by up to 88.57% and mobile genetic elements by 48.33–56.72% [62].

In addition to reducing ARGs, biochar positively impacts beneficial soil microbial populations and enzymatic activities, contributing to soil functionality. Biochar enhances the abundance of beneficial microbes such as *Subgroup 10*, *Bacillus* and *Pseudomonas*, which suppress harmful bacteria and promote plant growth [54]. For instance, in lettuce rhizosphere soil exposed to PS, genetic diversity decreased by 26.67%, but the application of peanut shell biochar increased gene abundance by 5.15%

compared to control soil [53]. Moreover, biochar integrated with microbial consortia has been shown to increase urease and dehydrogenase activities by 19.65% and 115.74%, respectively, in rubber crumb-contaminated soil [52]. Similar trends were observed with cotton stalk biochar in PVC-contaminated soils, although dehydrogenase activity increased only by 5–15%, indicating lower effectiveness compared to biochar integrated with microbial consortia [55]. Conversely, biochar derived from food waste showed a tendency to reduce urease and fluorescein diacetate activities, likely due to the heterogeneous composition of food waste, which results in inconsistent biochar properties and enzymatic effects [63].

Recent studies conducted between 2022 and 2024 on BC amendment in MP-contaminated soils have underscored its critical role in mitigating the adverse effects of MPs on soil ecosystems. BC facilitates these improvements by interacting with plants, activating genes associated with oxidative stress resistance, enhancing soil properties and promoting the growth of beneficial microorganisms, enzyme activity, and ARGs. Through these mechanisms, BC contributes to restoring microbial equilibrium, regulating enzymatic functions and modulating plant gene expression and ARG dynamics in the soil. Ultimately, these effects foster a healthier and more resilient soil ecosystem under MP contamination.

Water treatment

MP removal from aqueous media by BC adsorption

A summary of research on MP removal is provided in Table S2, Supporting Information File 1, covering a range of MPs, including PE, PS, polyamide (PA), and mixtures such as LDPE, polyethylene terephthalate (PET), PA, polycarbonate, PE, PS, and PVC [33,42,66,67]. Among these, PS is frequently utilized as a model MP due to its uniform composition and quantifiability, making it a reliable candidate for modeling and experimental investigations [33]. According to Shams et al. [68], PS exhibits a critical coagulation concentration of 800 mM NaCl, significantly higher than PE's 80 mM, which underscores PS's stability in saline environments and its suitability for long-term studies. The size of MPs is a critical factor regarding human health risks. MPs ranging from 40 to 4819 µm are typically excreted through human feces; however, MPs sized 20–103 µm can enter body fluids, and those averaging at 9.8 µm can infiltrate the liver. Even smaller MPs, ranging from 1 to 469 µm, can penetrate the heart and kidneys [69]. Therefore, the removal of increasingly smaller MPs has become an urgent focus in MP treatment research.

The treatment of PS using biochar derived from London plane tree pyrolyzed at 550 °C in a complete mixing model demonstrated an adsorption capacity of 60.05 $mg \cdot g^{-1}$, adhering to second-order reaction kinetics [42]. In another approach, filtration through biochar derived from banana peel achieved a removal efficiency of up to 92.16% for PS particles sized 150–300 µm [67]. An even higher removal efficiency, reaching 99%, was observed in a dual-layer filtration model utilizing silica sand and corn straw biochar for 10 µm PS particles [38]. For particles larger than 75 µm, mechanisms such as hydrogen bonding and hydrophobic interactions dominate, while smaller particles (<75 µm) are removed through π–π interactions between the benzene rings of PS and biochar surfaces, surface adsorption, hydrogen bonding, and surface complexation [67]. These findings highlight the potential of diverse biochar configurations for efficient MP removal under various conditions. Recent studies on biochar derived from coffee waste modified with amino-functionalized zeolite/phosphoric acid (AZP) highlight its potential for removing PS particles as small as 6 µm, with adsorption capacities ranging from 4.78 to 4.85 $mg \cdot g^{-1}$ [34]. Some studies have also reported MP removal for sizes below 1 µm. Specifically, PS particles ranging from 1 to 1000 nm treated with MBC achieved a maximum removal efficiency of 40.93% [39]. However, the study by Feng, et al. [43] reported that MBC derived from red mud mixed with lignin exhibited a removal efficiency for 100 nm PS particles ranging from 56% to 97.87%, depending on the MBC/PS ratio (0.01–10).

Magnetic biochar and Zn-modified magnetic biochar (MBC/MBC-Zn) further enhance removal through electrostatic interactions, forming metal–O–PS–MP bonds. These advanced materials demonstrated removal efficiencies of 96.24% and 84.77%, respectively, outperforming traditional biochar models like banana peel biochar, which achieved a removal rate of 96.5% for PS at a concentration of 0.2 g/L [70]. The integration of such mechanisms underscores the effectiveness of MBC and MBC-Zn in treating high-concentration PS systems.

For PE, current studies reveal high removal efficiencies of about 92–94% for both large microbeads (2–3 mm) and fine particles (10 µm) by BC [47]. For instance, Siipola, et al. [71] demonstrated near-complete removal of PE particles in fixed-column models using Scots pine bark and spruce bark, with adsorbent surface areas ranging from 187 to 603 $m^2 \cdot g^{-1}$. Similarly, filtration models employing palm kernel shell and coconut shell biochar showed performance highly dependent on biochar particle size and column dimensions [47]. Specifically, biochar sized 0.6–1.18 mm combined with a column diameter of 15 mm and a 20 cm bed depth achieved up to 96.65% removal efficiency. For 10 µm PE particles, retention was limited to segments 3–9 (out of 29 segments) with optimal removal observed for adsorbents with surface areas of 539 $m^2 \cdot g^{-1}$ [71]. Biochar derived from jujube waste pyrolyzed at 700 °C achieved more than 99% removal efficiency for PE, compared to 98% for biochar produced at 300 °C, at the optimal pH 7 [72]. Notably, PE removal efficiency was lower than that for nylon, particularly in pore volumes ranging from 1 to 11, due to differences in charge and surface interactions.

Conventional MP treatment models using BC include batch tanks and filter columns, as presented in Table S3, Supporting Information File 1. Based on statistical results depicted in Figure 6c, the MP removal efficiency using filter column models is 95.31% ± 5.26%, while the batch-modified BC model achieved 93.36% ± 4.92%. Fixed columns are highly effective for MP sizes of approximately 10 µm and larger, whereas batch methods are preferred for MPs smaller than 10 µm. The efficiencies of these two models are based on different mechanisms, as described in Figure 6. MP removal by BC filter columns is primarily facilitated by the fixation of particles through filtration effects, entanglement due to surface roughness and hydrophobic interactions [47]. The negatively charged surfaces of both biochar and PE interact via van der Waals forces, whereas positively charged nylon particles exhibit higher removal efficiency due to electrostatic π–π interactions with biochar [66]. The efficiency of batch-based MP removal is significantly influenced by the physicochemical properties of biochar, MP particle size and the aggregation potential of MPs [43,67]. These findings underscore the importance of optimizing biochar properties to enhance MP removal across different particle types and sizes. Despite advancements in biochar-based filtration and batch treatment, the removal efficiency for nanoplastics remains suboptimal. For instance, the adsorption capacity of biochar derived from London Plane bark for nanostyrene is limited to 60.05 mg·g^{-1}, while peanut shell biochar achieves only 16.47% removal efficiency [39,42]. However, modifications such as magnetic enhancement have improved filtration efficiency, with MBC reaching 40.86% removal. Moreover, MBC synthesized from red mud and lignin composites exhibits significantly enhanced adsorption performance, achieving 97.87% removal efficiency and a maximum

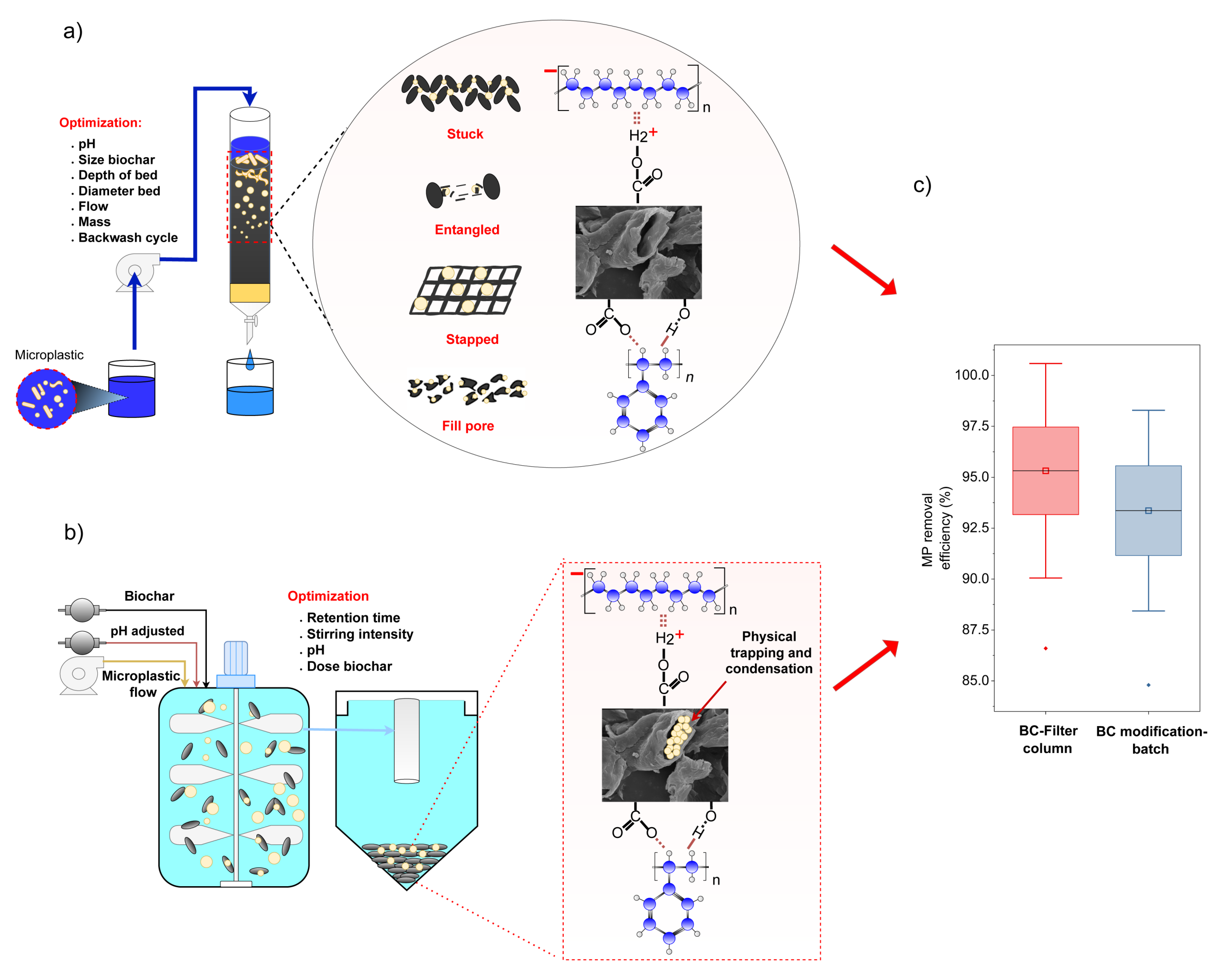

Figure 6: Mechanism of microplastic removal using biochar in a column filtration model.

adsorption capacity ($q_{\max}$) of 353.15 mg·g^{-1} for nano-PS (100 nm) [39,43]. These findings indicate that while different treatment models exhibit varying efficiency, the removal of nanoscale MPs predominantly depends on functional group interactions within biochar.

The presence of functional groups in AZP such as C–H, C–O, C=C, N–H, Al–O, and Si–O, along with its graphite-like structure, facilitates enhanced physical and chemical adsorption, as well as electrostatic interactions, thereby improving the removal of small MP particles [34]. Additionally, PS adsorption mechanisms suggest that MP self-polymerization and the strengthened metal–O bonding in nano-iron-modified biochar contribute to increased MP removal efficiency, particularly for nanosized particles [43]. Field studies on agricultural runoff reveal diverse MP contamination, including PVC films (500–1000 µm), fragments (45–500 µm, comprising PS, PA, PC, HDPE, LDPE, PET), and beads (40–48 µm, consisting solely of PE). Treatment using biochar derived from sugarcane achieved an overall removal efficiency of 92.6%, with the lowest performance observed for PET > PE > PA > ABS [66]. Hsieh, et al. [73] reported that PVC-contaminated water containing particles smaller than 10 µm could be effectively treated using a fixed-bed column. The filtration system employed sand as the primary medium, amended with 1% woodchip biochar produced at 700 °C, resulting in a removal efficiency of 92.91%.

Between 2022 and 2024, research on MP removal via biochar has increasingly focused on modified biochar to enhance the adsorption of small MP particles. These studies contribute to a deeper understanding of adsorption mechanisms based on biochar material properties. While these findings demonstrate significant progress in MP treatment, they also highlight the limitations of current research, which primarily focuses on single-component MP removal. Future efforts should emphasize developing tailored biochar materials for challenging MPs, such as PET and ABS, and addressing smaller particles below 10 µm to ensure comprehensive treatment in diverse environmental contexts.

Adsorption kinetics of MPs on biochar

Adsorption kinetics provide insights into the rate at which MPs adhere to biochar surfaces. Most studies employ pseudo-first-order (PFO) and pseudo-second-order (PSO) models to describe adsorption behavior [74]. The analysis of kinetic models for both biochar and modified biochar reveals that the correlation coefficient (R^2) for PSO is consistently higher than that for PFO, indicating that MP adsorption on biochar is primarily governed by chemisorption processes [75]. For instance, MP removal using MBC derived from red mud shows low R^2 values (0.14–0.23) for PFO but a significantly higher R^2 (0.99) for PSO, demonstrating the crucial role of metal–O functional groups in adsorption [43]. In contrast, the adsorption kinetics of AZP show minimal differences between PFO and PSO models, suggesting a balanced contribution from its graphene-like structure and Al–O/Si–O functional groups. The mixed first- and second-order model achieves an R^2 value of 1.0, further supporting this dual contribution [34]. Additionally, Li, et al. [33] reported that the Elovich model outperformed PSO, highlighting the role of heterogeneous surface interactions in MP adsorption onto biochar. The correlation analysis presented in Figure S2, Supporting Information File 1, demonstrates a strong inverse relationship between MP size and the second-order rate constant (k), with a coefficient of determination of 0.87 and a correlation coefficient of 0.93.

Comparison with other MP removal techniques

Various MP removal techniques in aqueous matrices, such as filtration, adsorption, and coagulation, have been extensively studied (Table S4, Supporting Information File 1). Among these, electrocoagulation demonstrates the highest removal efficiency (>98%) at an optimal pH of approximately 7 [76,77]. Although charcoal-based treatment for MPs smaller than 250 µm achieves a relatively high removal efficiency of 94.12%, its low adsorption capacity (4.5 mg·g^{-1}) necessitates the use of a large quantity of adsorbent to ensure effective removal [78]. Notably, aluminum anodes have shown superior performance compared to iron anodes, with removal efficiencies, varying according to MP type and size, of 98.4% for PP (1–2 mm), 98.2% for cellulose acetate (1–2 mm), 91.7% for PE (286.7 µm), and 93.2% for polymethyl methacrylate (6.3 µm) [77]. The dielectric properties of MPs also influence electrocoagulation performance; for example, PVC (insulator 10 × 10^5 Ω·cm) undergoes optimal treatment faster than PS (insulator 16 × 10^5 Ω·cm). Membrane filtration using PVDF in lab-scale experiments achieves 100% efficiency at a pressure of 2 bar; however, in industrial settings, efficiency drops to 54.6% due to high-pressure requirements [76]. Membrane fouling remains a major drawback, with ultrafiltration showing lower flux recovery compared to membrane filtration [79]. Biocoagulation using *Chlorella vulgaris* achieves a maximum removal efficiency of 73.01% for PS (65.49–328.4 µm), while *Spirulina platensis* reaches 81% for PS (328.4 µm) [80,81]. *Abelmoschus esculentus*-based biocoagulation achieves 64.46% and 80.11% efficiencies for PS and PVC (<100 µm), respectively [82]. While biochar and biocoagulation methods are environmentally friendly, their efficiency remains limited, particularly for MPs <10 µm. Furthermore, no studies have addressed the separation of biomass from MPs, whereas MP detachment from biochar is feasible during regeneration, allowing biochar to be reused effectively.

Electrocoagulation, despite its high MP removal efficiency and effectiveness for particles smaller than 10 µm, presents environmental challenges due to the production of metal-laden sludge. In contrast, biochar offers an environmentally sustainable alternative, leveraging agricultural waste while allowing for MP separation and biochar regeneration. These attributes highlight biochar's potential as a viable solution for MP remediation in diverse environmental contexts.

Practical implications and policy relevance

Bibliometric analysis serves as a useful tool for mapping research trends; however, its scope is constrained by its reliance on indexed publications within databases such as WOS, thereby limiting the comprehensiveness of the assessment [83,84]. This method primarily indexes citations and frequently referenced topics, providing macroscopic visualization rather than in-depth insights into specific research domains. Additionally, despite the support of specialized bibliometric software, the potential for subjective biases remains a concern, necessitating a critical and contextualized interpretation of results [85]. A deep and systematic understanding of the field is therefore essential to ensure precise evaluations.

Biochar and modified biochar have been widely recognized as promising materials for microplastic removal; however, their application at pilot or full-scale levels has not yet been extensively studied. As a result, uncertainties persist regarding the actual removal efficiency of these materials under real-world conditions. Furthermore, critical factors such as production costs and quality consistency have not been adequately addressed in current research. Existing policies related to microplastics predominantly emphasize plastic waste reduction and recycling, without establishing clear regulatory thresholds for microplastic concentrations in water and soil [86]. Given the well-documented environmental and biological hazards posed by microplastic pollution, biochar’s multifunctionality presents a promising approach for mitigation. Nonetheless, further research is required to bridge the gap between laboratory-scale studies and real-world applications, ensuring technological feasibility, economic viability, and alignment with future regulatory frameworks.

Conclusion and Future Perspectives

This paper provides a comprehensive overview of global research trends and recent progress in MP removal using biochar, based on a bibliometric analysis of relevant literature. The analysis highlights biochar as a promising solution, deserving extensive attention. The co-citation analysis and cluster views reveal the importance of interdisciplinary cooperation, suggesting that involving researchers from diverse scientific fields can yield valuable insights into tackling MP pollution. Despite its potential, significant practical challenges remain, necessitating further research to optimize biochar’s application.

Biochar has demonstrated remarkable potential in mitigating the impacts of MPs on soil and plants. It enhances plant biomass yield by up to 80%, improves soil water retention and cation exchange capacity and increases Olsen-P levels. It also fosters the growth of beneficial soil bacteria, such as *Subgroup 10*, *Bacillus*, and *Pseudomonas*, which suppress harmful microorganisms, reduce antibiotic resistance genes and enhance biodiversity. The increased activity of soil enzymes, including urease and dehydrogenase, further illustrates its role in improving soil fertility. Notably, microbial-enriched biochar exhibits the highest enzymatic activity, presenting significant opportunities for application in soil remediation.

In experimental setups for MP removal, biochar has proven highly effective. Modified biochars, such as magnetic biochar and Zn-modified biochar, enhance electrostatic interactions with MPs, achieving removal efficiencies ranging from 78% to 99%. Advanced biochar materials, including amino-functionalized zeolite series, have demonstrated the ability to remove MPs as small as 6 µm in batch systems. Promising results have also been obtained for nanoplastic removal using magnetic biochar, further demonstrating its adaptability as a remediation tool.

Despite significant progress, several critical challenges must be addressed before biochar can be widely applied for MP remediation. Optimization of surface properties remains essential to enhance removal efficiency, particularly for smaller MPs. The scalability of biochar applications requires further validation through pilot studies and field-scale implementation. Additionally, the integration of biochar with advanced treatment technologies, such as fluidized-bed systems, could enhance process feasibility.

Regulatory frameworks for MP pollution remain underdeveloped, necessitating standardized guidelines for permissible concentrations in environmental matrices. Evidence-based policies are required to support large-scale adoption while ensuring the safety and efficacy of biochar-based remediation strategies. The development of microbial-enriched biochar presents new opportunities for soil restoration, yet further research is needed to optimize its composition and stability.

Advancements in computational modeling, including machine learning and experimental design methodologies, could facilitate the optimization of biochar performance. The economic feasibility of biochar production remains a major concern, requiring cost-reduction strategies to enhance its practical applicability. Additionally, the potential release of contaminants during biochar synthesis and application must be carefully assessed to mitigate unintended environmental risks.

Future research should focus on addressing these challenges through interdisciplinary collaboration, ensuring that biochar-based approaches contribute to sustainable and effective MP mitigation strategies.

Supporting Information

Supporting Information File 1

Additional data.
[https://www.beilstein-journals.org/bjnano/content/supplementary/2190-4286-16-102-S1.pdf]

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Conflict of Interest

The authors declare no conflicts of interest.

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Tuan Minh Truong Dang: writing – original draft. Thao Thu Thi Huynh: data curation. Guo-Ping Chang-Chien: validation; visualization. Ha Manh Bui: writing – review & editing.

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Data Availability Statement

All data that supports the findings of this study is available in the published article and/or the supporting information of this article. Additional data can be made available upon reasonable request.

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Nanotechnology-based approaches for the removal of microplastics from wastewater: a comprehensive review

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Review

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Abstract

The increasing prevalence of microplastics (MPs) in aquatic environments has raised significant concerns due to their persistence, potential for bioaccumulation, and adverse effects on human and ecosystem health. Conventional wastewater treatment technologies are largely inadequate for effectively removing MPs, especially those in the nanosize range. This review presents a detail analysis of the sources, pathways, detection methods, and health impact of MPs, while emphasizing the emerging role of nanotechnology in their remediation. Nanomaterials, including nanoadsorbents, photocatalysts, and advanced membrane materials, exhibit unique properties such as high surface area, enhanced reactivity, and tunable surface chemistry, which offer promising avenues for the selective and efficient removal of MPs from water. This paper also explores the mechanism, performance and limitations of various nanoenabled treatment strategies such as adsorption, photocatalysis, and membrane filtration using materials like metal-organic frameworks, carbon-based nanomaterials, MXenes, and metal oxides. It also highlights recent innovations such as microrobotic systems and AI-assisted detection frameworks for MP monitoring. Despite high laboratory scale efficiencies, there are several challenges such as material scalability, environmental safety, regulatory frameworks, and real water applicability. This study proposes future directions for sustainable nanotechnology deployment, including green synthesis, hybrid system integration, and machine learning optimization. Together, these approaches aim to establish a comprehensive, scalable, and environmentally safe solution for the remediation of MPs in wastewater systems.

Introduction

Plastic pollution has become a crucial environmental concern recently. It was reported that from 1950 to 2015, global plastic production increased from 5 to over 300 megatons, with approximately 60 to 99 megatons turning into waste. It is estimated that, by 2060, the plastic waste generation could increase annually to 155–265 megatons. In spite of the continuous increase in the production of plastic, the rate of recycling remains low worldwide [1]. Microplastics (MPs) are tiny debris pertaining to plastic of size less than 5 mm. They are classified based on size, origin, and polymeric composition [2]. Morphologically, MPs appear as foam, beads, sheets, fragments, and fibres, with fibres being the most prevalent type, often originating from wastewater discharged by the textile industry. Based on their origin, MPs are divided into two groups, that is, primary and secondary. Primary MPs are intentionally produced in small sizes for the use in a range of products like cosmetics, clothing, and personal care items. In contrast, secondary MPs are formed when larger plastic items break down due to environmental factors like sunlight, physical wear, and microbial activity [3]. Common types of MPs found in ecosystems, particularly in freshwater and drinking water sources, include materials such as high-density polyethylene, polystyrene, polyvinyl chloride, and polypropylene [4].

Among the various contributors to MPs, residential households play a major role. Everyday plastic items ranging from toothbrushes over kitchenware to furniture, such as plastic chairs that are commonly used in homes, contribute to MPs release [5]. Wastewater treatment plants receive MPs primarily from two sources, namely, domestic sewage and industrial effluents. In domestic sewage, MPs typically originate from personal care and cosmetic products, as well as from laundering synthetic textiles. In contrast, industrial wastewater contains MP that are largely generated through the wear and tear of larger plastic items throughout their production, usage and disposal stages [6].

The tiny MP particles can directly harm marine life through ingestion or indirectly by attracting and accumulating environmental pollutants [7]. Experimental studies show that exposure to MPs can result in a wide range of harmful effects such as disruptions in metabolism, oxidative stress, immune system activation, developmental and reproductive toxicity, and damage to the nervous system [8].

MPs possess high specific area and strong adsorption capacity, enabling them to attract pollutants from the environment. They can accumulate harmful substances such as polycyclic aromatic hydrocarbons, heavy metals, and other toxic contaminants, increasing their potential risks to living ecosystems and organisms [9,10]. MPs have low density, variable sizes, high persistence, and non-biodegradable nature. These characteristics make their removal difficult, especially in aquatic environments [11]. Several studies have measured the presence of MPs in commonly consumed products such as alcoholic beverages, tap and bottled water, seafood, and salt. Reported concentrations vary, ranging from 0.10 to 1.48 MPs per litre in food items and between 4.23 and 94.37 MPs per litre in beverages [12]. The source of these contaminants includes airborne particles introduced during food processing or handling, degradation of plastic packaging, and, most significantly, contamination from polluted freshwater sources [13].

Primary, secondary, and tertiary treatment methods have been explored to mitigate MP contamination. Meanwhile, a more sustainable solution remains essential for the future. In recent years, extensive research has focused on several processing technologies, including coagulation, advanced oxidation processes, microbial degradation, membrane bioreactor, rapid sand filtration, and dissolved air flotation [14,15].

The publication trend over the past decade, as illustrated in Figure 1, demonstrates a significant rise in research activities focused on the removal of MPs and nanoplastics (NPs). Figure 1a, based on a keyword search from Elsevier's database, reveals a consistent year-on-year increase in the number of publications related to MP removal from 2015 to 2025. Notably, the number of studies surged from just 80 in 2016 to a peak of 3616 in 2024. A similar trend, though less pronounced, is observed for NP removal, which also showed a steady growth, rising from 48 publications in 2015 to 1039 in 2024. This indicates a growing recognition of NPs as emerging contaminants, though they still receive less attention than MPs. In contrast, Figure 1b provides insights from Springer Nature, categorizing the type of publications related to both MP and NP removal between 2015 and 2025. Research articles dominate the landscape, with 1478 publications focused on MPs and 325 on NPs. Review articles and book chapters also show substantial number of MP studies, suggesting a mature and well-reviewed body of literature. In contrast, contributions on NPs remain limited across all categories, reflecting the relatively nascent stage of this research area. Together, these figures underscore a growing scientific interest in plastic pollution, with a marked focus on MPs. However, the emerging concern around NPs present an opportunity for further in depth research and exploration.

Advancements in synthesis and characterisation techniques have enabled the detection of materials at the nanoscale, unlocking new opportunities across various streams. In the field of water treatment, nanotechnology is gaining wide attention due to its enhanced efficiency, effectiveness, affordability, and durability. The key properties of nanoparticles include high surface area, extensive functionalization, high reactivity, and size-dependent characteristics. By leveraging these properties, water treatment methods can be refined at the nanoscale to selectively target pollutants [16,17].

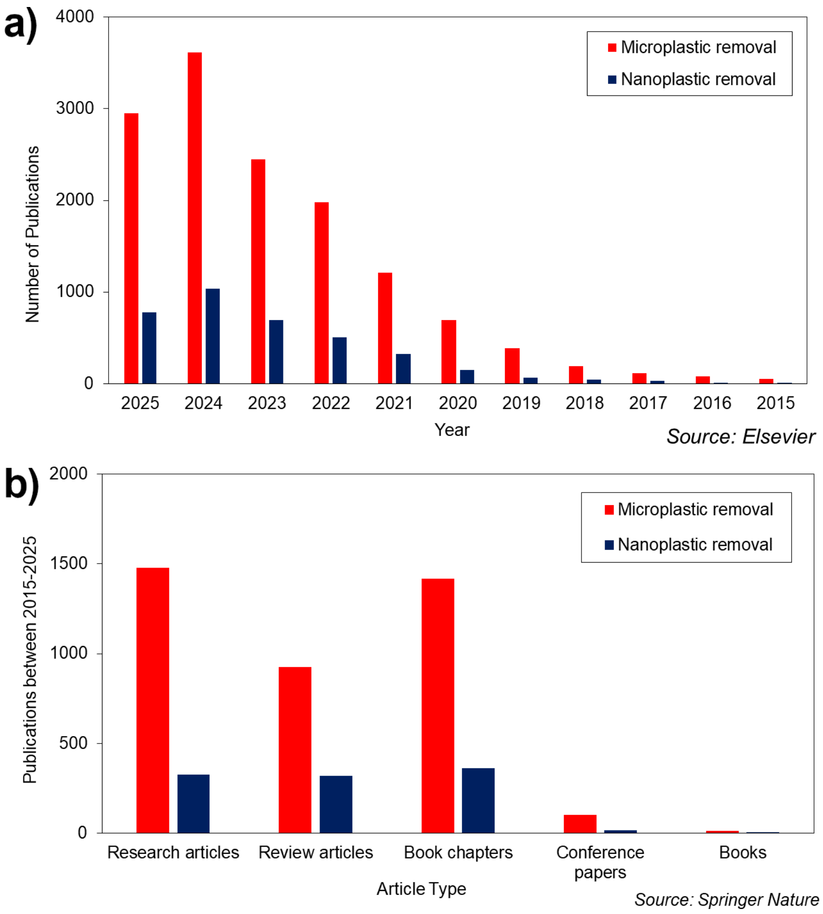

Figure 1: (a) Number of publications in the past decade with MP and NP removal keyword search from Elsevier, (b) number of publications in the past decade with MP and NP removal keyword search from Springer nature.

This comprehensive review explores the potential of nanotechnology in removing MP contamination from water and wastewater. Unlike conventional treatment methods, which are less effective in capturing nanoscale plastic pollutants, nanotechnology-based approaches offer precision, enhanced adsorption, and catalytic degradation capabilities. By combining the principles of water treatment technologies and nanoscience, this study highlights innovative pathways for improved removal efficiency, selective pollutant targeting, and sustainable application. As the global concern over plastic pollution is a rising concern, this review sets the stage for the next generation of water treatment strategies, focusing on the application of nanotechnology for the production of safer and cleaner water resources.

Review

Source, pathway and detection of MPs in water and wastewater

MPs are formed through primary processes and from secondary sources [18]. Figure 2 represents the different sources of MPs.

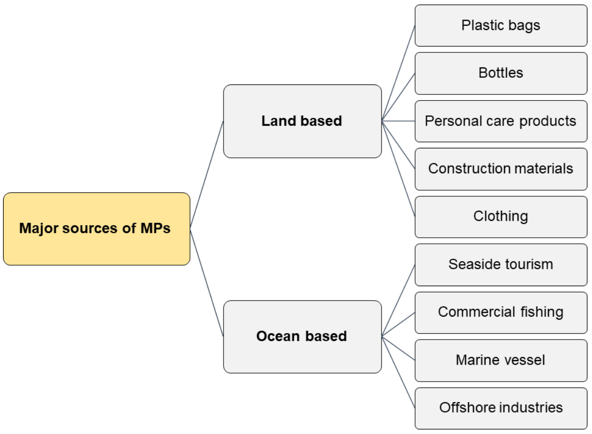

Figure 2: Different sources of MPs.

The marine environment is considered as the primary sink of MPs. MPs that are generated on land are eventually transported by various modes, including surface runoff and streams, and find their way to ocean. In oceans, these particles with low density are present initially in the suspended form. However, as time passes, they interact with suspended clay particles, and an accumulation of biofilm occurs, resulting in an increase in density. This will result in gradual settlement of the MPs in the sediment [19]. The concentration of MPs in wastewater varies, with levels reaching several hundred particles per litre [7]. Studies have reported significant variation in the concentration and types of MPs present in wastewater samples collected from different treatment plants. Commonly identified MPs include polyethylene (PE, 4–51%), polyester (PES, 28–89%), polystyrene (PS) (5–27%), polyethylene terephthalate (PET, 4–35%), polypropylene (PP), and polyamide (PA, 3–30%) [20]. In a study performed by Steinfield et al. [21], it was observed that the MP concentrations in untreated wastewater from paper mills range from 10^6 to 10^8 (MPs ≥ 20 µm/m^3). The paper mills studied, manufacture a variety of paper products, including tissue paper, cardboard, and specialized items, using different raw materials and polymeric additives like polymeric fibres and coating colours. It was observed that, in paper mill waste, the polymeric additives are the predominant source of microplastic.

In a study performed by Liu et al. [22], it was observed that the petrochemical industry plays a major role in microplastic pollution. Crude oil undergoes extraction, refining, and cracking to yield low-molecular-weight monomers like ethylene and propylene. These monomers are later polymerised to produce various plastic materials. This results in the release of microplastic particles, which enter into wastewater treatment facilities through industrial effluents.

Wastewater treatment plants (WWTPs) are the major contributors to microplastic pollution in the environment. They serve as critical points for collecting and filtering MPs from domestic sewage, storm water runoff, and industrial effluents. However, conventional WWTPs often fail to completely remove MPs, leading to MP discharge into natural water bodies [23]. The primary sources of MPs in wastewater treatment plants include plastic-based industrial effluents, synthetic textile fibres from clothing, personal care products in household wastewater, wear and tear of road tires, and discharges from textile manufacturing [9]. Table 1 lists some of the MP sources in wastewater with the corresponding concentrations. In aquatic environments,

Table 1: MP concentration and detection method in wastewater.

Source	MPs dimension	MPs detection method	Dominant microplastic type[a]	Concentration	Ref.
primary sludge and biosludge from paper and pulp industry	<20 µm	Raman spectroscopy	PE, PP	primary sludge: 900–1600 MPs/g dry weight biosludge: 210 MPs/g dry weight	[25]
WWTP in antarctica	<50 µm	micro-Raman spectroscopy	PP, PVC, PTFE, PET, PS	64 to 159 particles per litre	[26]
secondary WWTP located on the river Clyde, Glasgow	–	–	Microbeads	15.70 ± 5.23 particles per litre	[27]
drinking water treatment plant	0.5–0.1 mm and 5–1 mm	–	wastewater dominated by synthetic fibre (polyester type), while drinking water was characterised by fragments and fibres	2–11 particles/m^3	[28]
WWTP of an organized industrial zone, Bursa	fibre, 500–1000 µm	–	PE, PY, PET, PP	480–801 particles/m^3	[29]
inlet of WWTP Guheshwori, Kathmandu city, Nepal	fibre, fragments, foam, and pellets, 500–150 µm size	–	–	31.2 ± 17.3 particles per litre	[30]
hospital laundry wastewater Copenhagen, Denmark	100–200 µm	–	–	1.4 × 10^6 particles per litre	[31]
reclaimed WWTP	–	Raman spectroscopy	–	0.75 ± 0.26 particles per litre	[32]

Table 1: MP concentration and detection method in wastewater. (continued)

Kappala wastewater treatment plant in Sweden	–	FPA-μ-FTIR, ATR-FTIR, and stereoscopic microscope	–	6.42×10^{10} counts/day	[33]
effluent of WWTP, Portugal	–	μ-FTIR and microscope	–	52–233 particles per litre	[34]
WWTP, Denizili, Turkey	fibres in 100–500 μm	μ-FTIR and visual sorting	PE, PVA	140 particles per litre	[35]
influent of Farabi Hospital WWTP, Iran	<0.5 mm	SEM, FTIR, stereomicroscope	PP, PE, Latex, PU, PS, PA, Nylon, HDPE	23 particles per litre	[36]
sewage treatment plant, China	0.22 to 5.0 mm	TD-GC/MS	PE	Influent: 1313.11 ± 336.96 μg/L Effluent: 25.84 ± 3.75 μg/L	[37]
influent of M'zar WWTP located in Agadir metropolis	100–500 μm	stereoscopic microscope, ATR-FTIR and SEM-EDX	PE, PP and PS	519 MPs/L	[38]
influent of WWTP sited in Southwest Europe	>500 μm	stereomicroscopy and FTIR spectrophotometry	PE, PET and PP	16.1 ± 3.3 MPs/L	[39]
influent of WWTP in Danang, Vietnam	1.6 to 5000 μm	FTIR	PE, PET, Nylon and PVC	183–443 MPs/L	[40]
municipal WWTP in Thailand	0.05–0.5 mm	optical stereomicroscope and FTIR	PET, PE, PP	77 ± 7.21 MPs/L	[41]
sewage treatment plant, Bihar	<250 μm	optical microscope, FESEM-EDX and ATR-FTIR	LDPE	64.3 ± 4.89–47.66 ± 4.71 MPs/L	[42]

[a]PP – polypropylene, PVC – polyvinyl chloride, PTFE – polytetrafluoroethylene, PET – polyethylene terephthalate, PS – polystyrene, PE – polyethylene, PY – polyester, PU – polyurethane, PA – polyamide, HDPE – high-density polyethylene, LDPE – low-density polyethylene.

MPs transform due to the mixing with aggregates, biofouling, and leaching of additives. These alterations affect their buoyancy, leading to their accumulation in benthic ecosystems [24].

Impact of MPs on health and ecosystems

In smaller organisms like plankton, MPs have severe impact because of their small size, widespread presence, and ability to absorb pollutants [43]. Once consumed, MPs may cause physical harm to organisms, restrict food intake and interfere with plankton feeding [44]. Additionally, they can also damage the digestive tract, potentially affecting plankton development, lifespan and reproduction, and growth [45]. MPs function as carriers for heavy metals, resulting in their accumulation in the digestive systems of fish. This accumulation can negatively affect fish by impairing their activity, stunting growth, disrupting reproduction, and potentially leading to mass mortality. Such interactions amplify the ecological consequences of MPs in the environment. Consequently, the ingestion of MPs embedded with contaminants can contribute to the transfer of toxic substances across terrestrial and aquatic food webs [46].

In freshwater ecosystems, MPs can adhere to plant tissues and subsequently transfer to herbivores that consume these plants. In a food chain, as MPs move from lower to higher trophic levels, they accumulate in animal tissues, leading to bioaccumulation. Because of this, freshwater organisms are often considered effective bio-indicators of MP contamination [47]. In a study performed by Raza et al. [48], it was seen that, MPs, particularly polyacrylamide, pose significant risks to aquatic environments by accumulating in fish tissues, disrupting antioxidant enzyme activity, and altering blood parameters. Their presence leads to oxidative stress, histological damage in vital organs, and overall impaired fish health, highlighting their toxic impact on aquatic ecosystems. NPs and MPs negatively impact marine organisms, but their toxicity toward marine bacteria remain less understood. In a study performed by Sun et al. [49], it was found that polystyrene NPs, more than MPs, inhibited the growth of *Halomonas alkaliphila*, disrupted ammonia conversion, and induced oxidative stress. These findings highlight the effect of plastic debris on marine microbial functions, potentially disrupting nitrogen cycles and ecological balance.

When MPs enter the bodies of animals and humans through the food chain, they cause health problems including reduced birth rates, disruptions in the reproductive systems, altered sex ratios, and abnormal changes in body weight [45]. Understanding how MPs enter and affect the human body is essential, as their small size allows them to penetrate various biological barriers. MPs smaller than 5 µm can reach the alveoli, enter the circulatory system, and accumulate in the organs such as the brain, lungs, liver, spleen and digestive system. Those around 10 µm can breach cell membranes and the placental barrier, while MPs of 20 µm can reach internal organs. Exposure occurs through inhalation, posing risks to adults, while children face dangers from MPs in contaminated drinking water. Once inside the body, MPs can trigger neurotoxicity, cytotoxicity, oxidative stress, immune response, metabolic disruption and DNA damage [47]. According to a study conducted by Kumar et al. [50], humans are exposed to these MPs through various pathways, including seafood, water, agricultural products and beverages. MPs, along with toxic chemicals like polycyclic aromatic hydrocarbons and polychlorinated biphenyls, have been linked to reproductive, immune, and digestive systems through inhalation, ingestion, and dermal exposure. Polystyrene and polyvinyl chloride have been detected in human implants and are associated with carcinogenic effects. These plastics can induce oxidative stress, cytotoxicity, DNA damage, metabolic disruption, and immune responses, highlighting the urgent need for further research on their health impacts. Figure 3 shows various impacts of MPs on human health and environment.

Removal of MPs from wastewater

Figure 4 depicts various techniques for the removal of MPs from aqueous environments. Conventional approaches for removing MPs from water rely on a combination of physical, chemical and biological process [51]. Physical methods primarily facilitate the separation of larger plastic particles based on size and density [18]. Chemical processes are employed to destabilize and aggregate plastic particles, enhancing their removal through settling or filtration [52]. Biological treatments can entrap or partially degrade plastics via microbial activity, though typically with limited efficiency for persistent polymers. Advanced oxidation processes offer a more robust route for plastic degradation by generating highly reactive radicals through techniques such as Fenton and photo-Fenton reactions, UV/H_2O_2 systems, ozonation, TiO_2, photocatalysis, and electrochemical oxidation [53]. These methods hold potential for breaking down MPs into smaller, less harmful by products, although optimization and scalability remain ongoing challenges.

Physical processes

Various membrane filtration technologies have been employed to mitigate MP pollution, including microfiltration, membrane bioreactors, reverse osmosis, dynamic membranes, and ultrafiltration. Additionally, media filtration techniques, such as sand filtration and activated carbon particle filtration, have been utilized in drinking water treatment plants to enhance MP removal [54].

Chemical processes

Chemical treatment involves the use of specific reagents that initiate a series of chemical reactions aimed at enhancing the

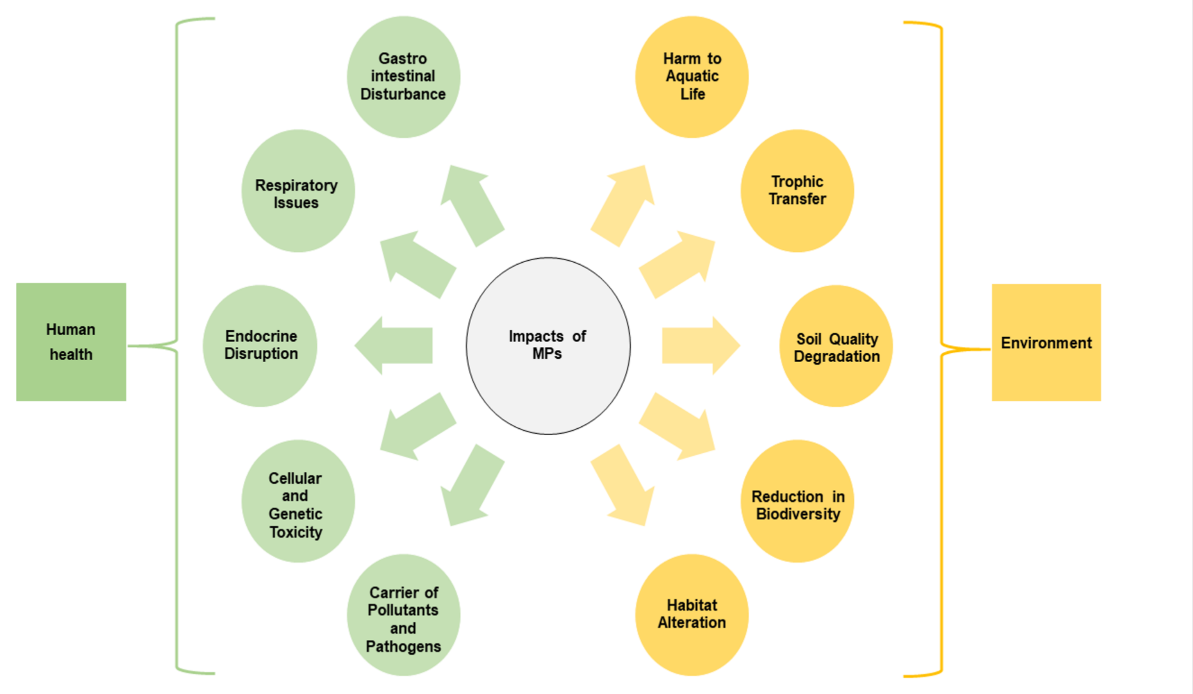

Figure 3: Impact of MPs on human health and environment.

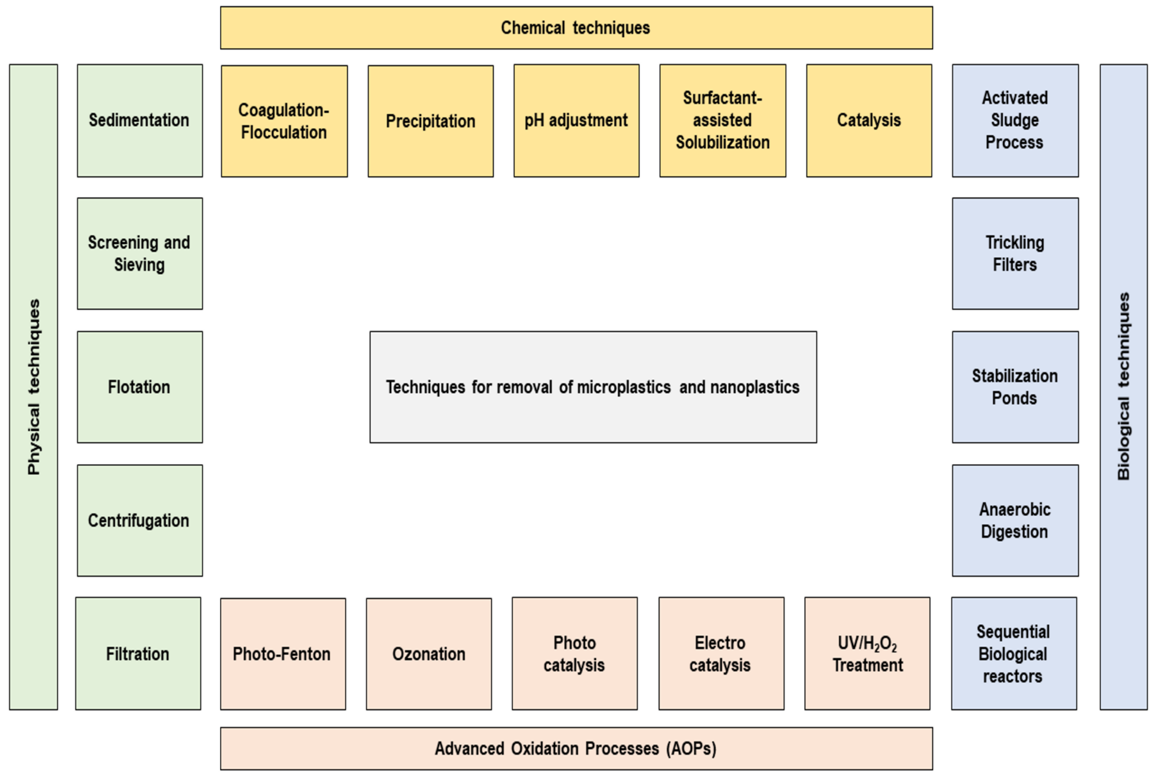

Figure 4: Common treatment methods for the removal of MPs from wastewater.

purification of water. This approach is particularly useful in removing MPs that are not effectively eliminated through physical or biological methods. During the chemical treatment, compounds are introduced to either break down MPs or facilitate their removal. These methods work by transforming MPs into less hazardous substances. Common chemical treatment techniques include coagulation, flocculation, precipitation, and electrocoagulation [18]. Even though both physical and chemical methods are found to be effective in the removal of MPs, they pose several challenges on the remediation of MPs, such as blocking pores and surfaces of membranes and increased amounts of coagulants [55].

Biological processes

Various microorganisms, including *Bacillus*, *Actinobacteria*, *Pseudomonas*, *Aspergillus*, *Penicillium*, *Cyanobacteria*, and different species of microalgae, have demonstrated the ability to degrade MPs such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), PET, and polyester. These microorganisms have been identified in environments heavily contaminated with plastics, such as municipal landfills, dumpsites, polluted water bodies, and even in the digestive systems of plastic-feeding insects. Advances in biotechnology have further enabled the development of genetically modified organisms to enhance MP degradation. However, a significant concern with microbial biodegradation is the potential ecological impact of introducing these organisms into non-native environments, which may lead to unforeseen consequences. Additionally, some microorganisms produce toxic by-products during degradation, but this challenge can be addressed through the use of microbial consortia [56].

Advanced oxidation processes

Advanced oxidation processes (AOPs) represent a category of water treatment technologies that utilize reactive radical oxidation mechanisms. These processes generate reactive oxygen species (ROS) through methods such as photocatalysis, ozonation, and electrochemical activation, which effectively break down the polymer chains of MPs, leading to their mineralization. The primary AOP techniques used for removing MPs from water include ultraviolet-induced oxidation, ozone-based oxidation, photocatalysis (activated by UV, solar, or visible light), electrochemical oxidation, and persulfate-activated oxidation [57]. In photocatalysis, photons excite the catalyst, generating electron–hole pairs that trigger redox reactions with the pollutants adsorbed on its surface. In Fenton and Fenton-like processes, hydroxyl (•OH) radicals are formed when hydrogen peroxide reacts with a metallic active phase, such as Fe^{2+}, facilitating the oxidation and breakdown of contaminants [58]. Table 2 depicts the advantages and limitations of various techniques for the removal of MPs.

Nanoparticle-based removal

Advancements in characterization and synthesis techniques have enabled the manipulation of materials at the nanoscale, leading to innovations across various domains, including energy, electronics, and biomedical applications. Figure 5 depicts various techniques for synthesis of nanoparticles. Nanoparticle synthesis is essential for tailoring materials that effectively remove MPs. Various approaches allow researchers to customize structure and functionality based on application needs. For example, the sol–gel process transforms a colloidal

Table 2: Techniques for removal of MPs and NPs from aqueous environments.

	Technique	Mechanism	Advantages	Limitations	Ref.
physical processes	sedimentation	allows particles to settle based on density difference between MPs and water	cost effective; suitable for large MPs	ineffective for smaller MPs and time consuming	[59]
	flotation	air bubbles adhere to MPs	quick operation, little space needs, adaptability of use, and moderate price	reagents for flotation, a hydrophobic surface, and entrainment of organic pollutants are all necessary	[18,60]
	centrifugation	MPs/NPs removed based by centrifugal force	rapid and efficient separation; scalable	energy-intensive; less effective for MPs with lower settling velocity	[61,62]
	filtration	MPs are physically trapped by means of a filter medium	adapted and customised to different scales; does not require chemical additives	clogging of filters and limited performance for very small MPs and NPs	[62]
	adsorption	materials with high affinity to MPs adsorb them to surfaces facilitating removal	high removal efficiency; can be regenerated and reused; removes other pollutants	low selectivity, prepared using an adsorbent	[63]
chemical processes	coagulation-flocculation	neutralizing charge of colloidal particles and subsequent removal through filtration	cost-effective; widely adopted	enormous amount of sludge generation	[18]
	electrocoagulation	electric current destabilizes and agglomerates microplastic particles	capable of removing other pollutants; scalable	electrode fouling less efficient for small particles	[64,65]
biological processes	activated sludge	MPs entrapped in microbial flocs followed by degradation and sludge formation	good removal efficiency	removal efficiency varies	[27,66]
	anaerobic–anoxic–aerobic activated sludge	removes MPs by a combination of anaerobic, anoxic, and aerobic zones, along with different sludge return strategies	cost effective; short hydraulic retention time	low removal rate; time consuming; generates substantial amount of sludge	[67,68]
	enzymatic degradation	Enzymes employed to degrade MPs	Efficient degradation of MPs	high cost; intricate process for enzyme development	[67,69]
	biodegradation	extracellular enzymes secreted by microbes depolymerise MPs	partial or complete degradation	low efficiency; time consuming	[54]
	membrane bioreactor	removal by perm-selective membrane along with biological process	easy integration with other processes; fine filter precision	poor removal of smaller MPs; high treatment cost	[18,54]

Table 2: Techniques for removal of MPs and NPs from aqueous environments. (continued)

advanced oxidation processes	photo-Fenton	iron salts and H_2O_2 with UV generate hydroxyl radicals that degrade MPs	environment friendly and sustainable	requires UV and pH control; iron sludge formation	[70,71]
	ozonation	microplastic polymer can be split into functional groups that contain oxygen	low cost and high efficiency	high production cost; Environmental issues	[18,72]
	photocatalysis	generate ROS upon exposure to light	eco-friendly, long-lasting	requires a lot of energy (ultraviolet light)	
	electrochemical oxidation	electric current induced chemical reactions degrade MPs	high efficiency, degrading a number of organic contaminants, not requiring the addition of chemical agents, and not producing sludge	high cost of electrodes	[73]
	plasma treatment	plasma generates reactive species that chemically degrade MPs	have significant potential microplastic pollution	–	[62]

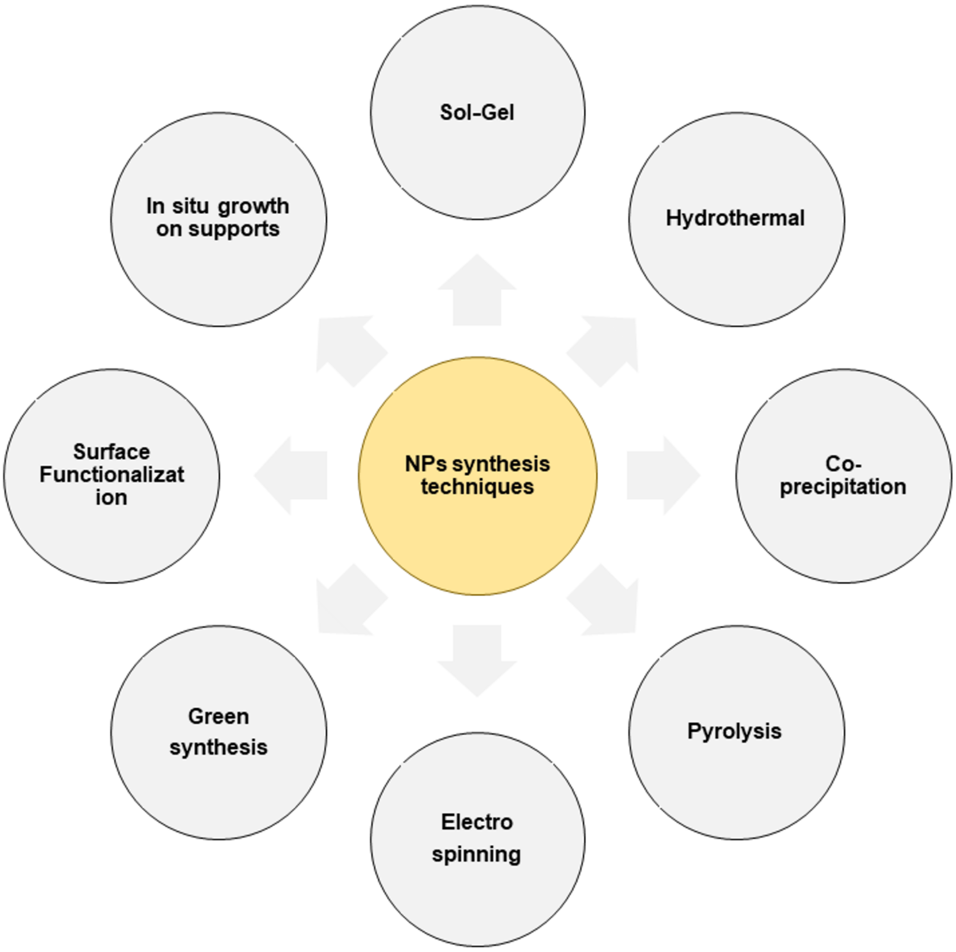

Figure 5: Different methods for synthesis of nanoparticles.

solution into a gel, enabling precise compositional control and producing homogenous metal oxides suited for photocatalytic applications [74]. Hydrothermal synthesis uses high-temperature, high-pressure aqueous environments to yield well crystalized particles with controlled morphologies, while co-precipitation involves solvent displacement method, where acetone, ethanol, hexane are some of the solvents used [75]. In electrospinning, nanofibers are generated [76]. In parallel, green synthesis utilises biological entities such as plant extracts or microorganisms as reducing agents to produce eco-friendly nanoparticles, minimizing the used of hazardous chemicals [17]. Together, these techniques offer versatile strategies for developing nanomaterials that can be fine-tuned to optimize microplastic removal efficiency while adhering to sustainable practices.

In the field of water treatment, nanotechnology has been recognized for enhancing efficiency, affordability, effectiveness, and durability. These benefits stem from unique properties such as high specific surface area, increased reactivity, extensive functionalization, and size-dependent behaviour. By leveraging these characteristics, water treatment processes can be fine-tuned at the molecular or atomic level to selectively target specific contaminants [16]. Figure 6 illustrate the key mechanisms of MP removal using nanoparticles.

Nanoparticles as adsorbent: Adsorption is the most commonly used method for eliminating inorganic and organic pollutants from water and wastewater [77-81]. However, traditional adsorbents often exhibit limitations such as poor selectivity, low specific surface area, a limited number of active sites, and slow adsorption rate. In addition, regeneration cycles and short adsorption can affect the cost-effectiveness of the process. The removal of MPs by adsorbents primarily relies on hydrophobic interactions, electrostatic attraction and hydrogen bonding, which are influenced by their surface characteristics. Among various adsorbents, activated carbon and biochar have gained wide attention for treating water contaminated with MPs. Meanwhile, a higher cost of these adsorbents limit their use for the removal of MPs [82]. Research is actively exploring alternative adsorbents, with a particular focus on nanomaterial-based options. Among these, carbon nanotubes (CNTs), nanoscale

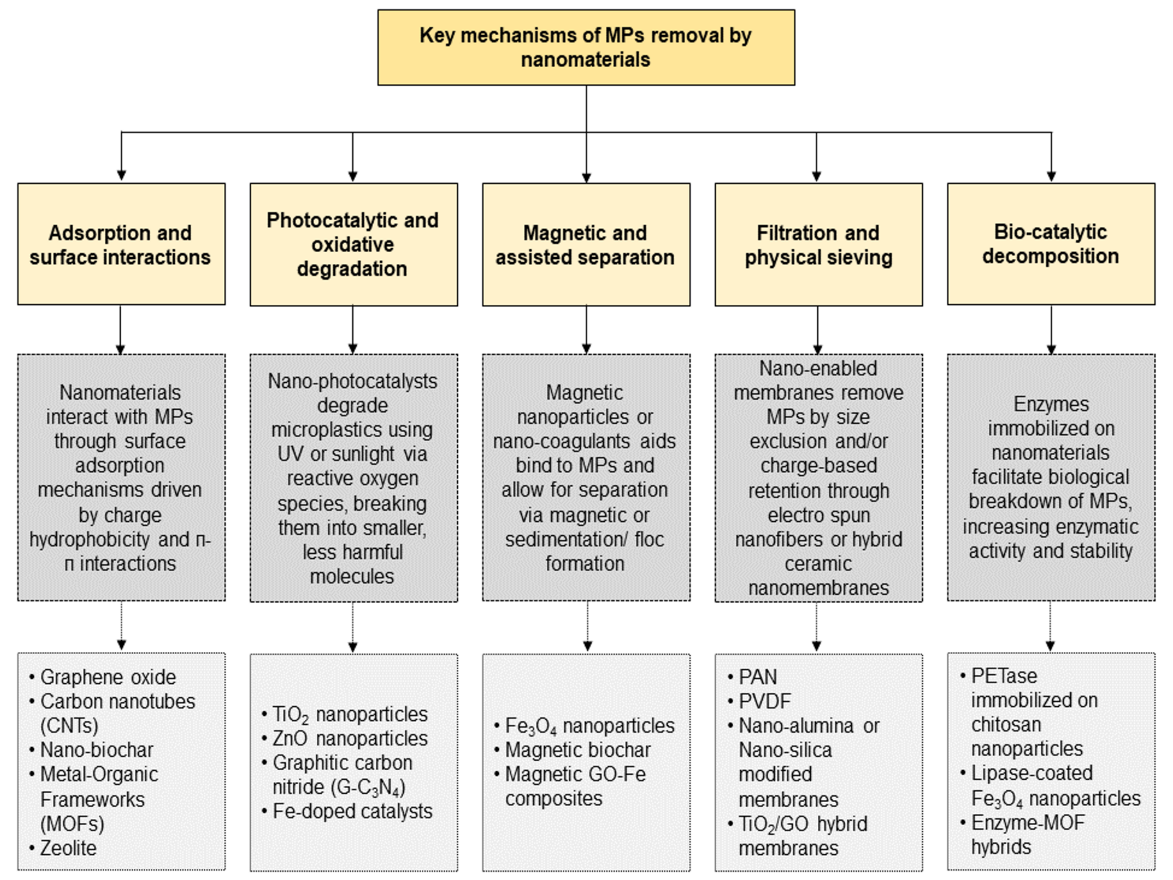

Figure 6: Key mechanisms of MP removal using nanoparticles.

metals, nanocomposites, and metal oxides offer a promising approach [55]. Nanoadsorbents possess a higher specific surface area and a large number of active sites, contributing to their rapid processing, enhanced selectivity, and extended adsorption–regeneration cycles [80]. In addition, nanomaterials also exhibit excellent reactivity, adaptability for functionalization and superior sorption capacity.

Carbon materials with graphene-like structures, made up of sp^2-hybridized carbon atoms, have gained considerable interest for their use in water treatment technologies. Their abundance of functional groups, expansive surface area, and inherent hydrophobic nature make them highly effective in capturing various organic pollutants, including methylene blue, neutral red, and polycyclic aromatic hydrocarbons. Notably, the unique hexagonal honeycomb crystal structure imparts exceptional stability, allowing them to perform efficiently under challenging environmental conditions and across a wide pH range, making them reliable materials for pollutant removal [83]. Sun et al. [84] studied the removal of MPs from water using a sustainable adsorbent composed of graphene oxide and chitin. The elastic nature of the sponge retains its high porosity, enabling consistent and efficient adsorption across reuse cycles.

Layered double hydroxides (LDHs) are a distinctive group of 2D inorganic materials known for their remarkable physical and chemical characteristics. Their exceptional ion exchange ability, large surface area, high thermal stability, and customizable structural features have made them valuable in water purification process [85]. When subjected to heat, LDHs release interlayer water and anions. This results in the formation of double-layered oxides (LDO). Both LDO and LDHs have shown effectiveness in adsorption processes for removing organic pollutants, including MPs [86]. Figure 7 illustrate the various types

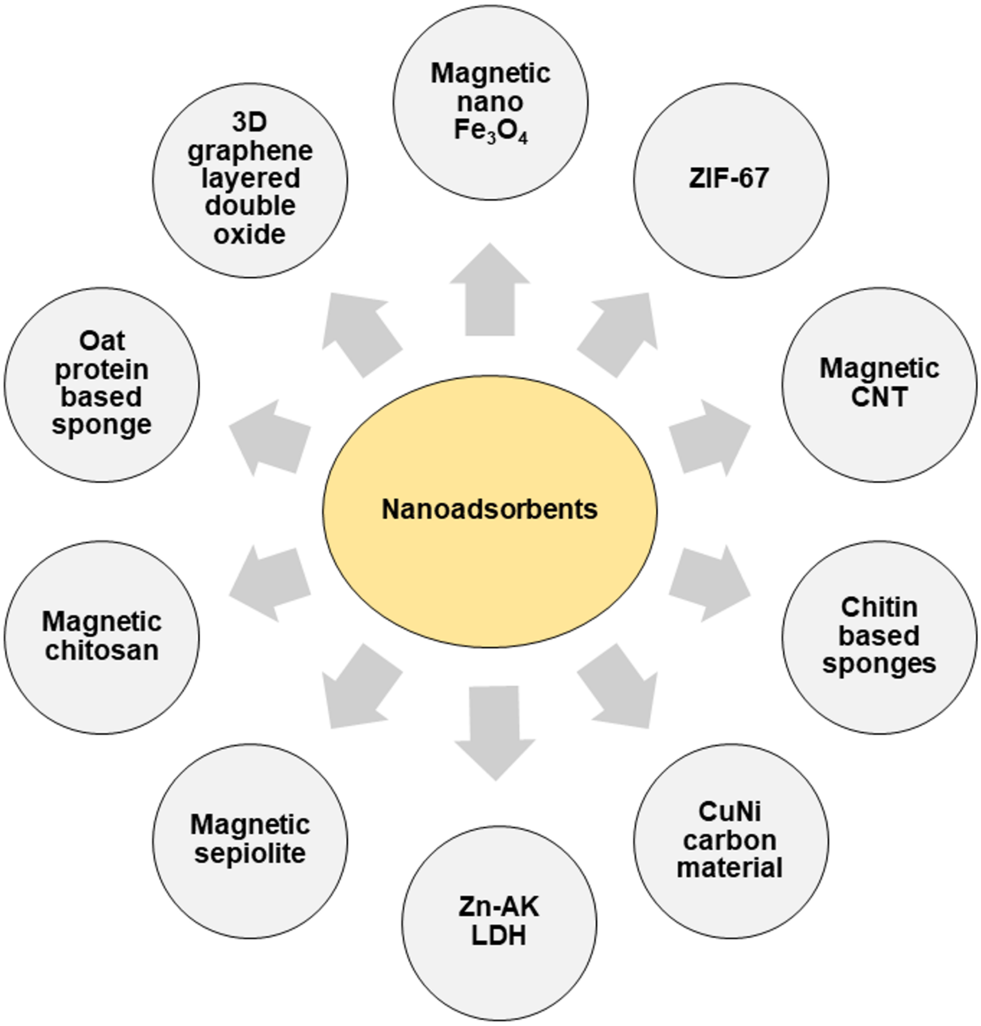

Figure 7: Different types of nanoadsorbents used for the treatment of MPs.

of nanoadsorbents used for MP removal, while Table 3 present their operational conditions and corresponding removal efficiencies for different types of MPs.

Nanoparticle-based photocatalysis: Catalytic or photocatalytic oxidation, categorized under AOPs, is an effective method for eliminating trace pollutants and harmful microorganisms from water. Beyond this, photocatalysis serves as a valuable pretreatment technique, promoting the breakdown of persistent and toxic substances. It can also enhance the efficiency of subsequent chemical or biological treatments aimed at removing organic contaminants [96]. In photocatalysis, under UV illumination, electron–hole pairs are generated. These pairs interact with water molecules and dissolved oxygen to generate reactive oxygen species, such as hydroxyl radicals and superoxide anions. These highly reactive radicals act as strong oxidizing agents, attacking pollutants by breaking their chemical bonds, ultimately leading to their degradation and mineralization [97]. For a compound to undergo oxidation using a photocatalyst, its redox potential should be higher than the valence band edge of the semiconductor catalyst. In contrast, for reduction to occur, the redox potential must be lower than the conduction band edge. This is because, upon excitation, holes generated in the valence band participate in oxidation reactions, whereas the electrons excited to the conduction band drive the reduction processes [96].

The particle size of photocatalysts plays a very important role in the recombination of electrons and holes. Smaller particles exhibit higher photocatalytic activity due to their increased surface area, which allows for greater adsorption of pollutants and enhanced production of hydroxyl radicals. These benefits are particularly significant when the particle size is reduced to around 10 nm. Utilizing nanostructured semiconductors in photocatalytic applications proves to be more efficient, as a larger proportion of the photogenerated electron–hole pairs is available at the surface. Nanoparticles, owing to their high surface-to-volume ratio, demonstrate superior catalytic performance compared to bulk materials. Furthermore, the particle size of semiconductors influences their bandgap energy and crystalline structure, which in turn affects their redox potential and the spatial distribution of photo-induced charge carriers [98].

Tofa et al. [99] studied the photocatalytic activity of ZnO nanorods for breaking down LDPE, a common microplastic found in wastewater. Experimental results led to the proposal of a detailed degradation pathway. The process initiates when

Table 3: Nanoadsorbents for the removal of MPs and NPs.[a]

Nano adsorbent	MPs	Conc.	Adsorbent dosage	Sample pH	Contact time (min)	Max removal efficiency (%)	Kinetics	Isotherm	Ref.
magnetic nano-Fe_3O_4	PE, PP, PS, PET	0.5 g/L	1.3 g/L	–	150	>80%	–	–	[87]
ZIF-67	PS	5 mg/L	0.4 g/L	8	20	92.1	PFO	FI	[88]
magnetic CNT	PE, PET	5 g/L	5 g/L	–	300	100	–	–	[89]
chitin-based sponges	C-PS, A-PS and PS	1 mg/L	–	6–8	–	92.1%	–	–	[90]
CuNi carbon material	PS	10 mg/L	0.3 g/L	–	–	99.18%	PFO	LI	[91]
Zn-AK LDH	PS	250 mg/L	5 mg	4	120	100	GO	FI	[92]
magnetic sepiolite	PE, PP, PS, PET	10 g/L	0.8 g	–	10	98.4	–	–	[93]
polydopamine-enhanced magnetic chitosan	PET, PE, PS	300 mg/L	–	6–9	1440	97.3	PSO	FI	[94]
G@LDO	PS	100 mg/L	1 g/L	3–11	720	>80	PSO	LI	[83]
oat protein-based sponge	PS	1 mg/L	20 mg	4	–	85	PSO	LI	[95]

[a]PE – polyethylene, PS – polystyrene, PET – polyethylene terephthalate, C-PS – carboxylate modified polystyrene, A-PS – amine modified polystyrene, PFO – pseudo first order, GO – general order, PSO – pseudo second order, FI – Freundlich isotherm, LI – Langmuir isotherm, G@LDO – 3D graphene-like carbon assembled layered double oxide material.

hydroxyl and superoxide radicals attack weak points in the polymer chains, typically structural flaws or chromophoric sites. This attack generates low-molecular-weight alkyl radicals within polyethylene. These reactive species then trigger various transformations, including chain cleavage, branching, cross-linking, and oxidation. Interaction with oxygen forms peroxy radicals, which extract hydrogen atoms from the polymer backbone, creating hydroperoxide intermediates. These intermediates break down into alkoxy radicals, which further react to produce carbonyl and vinyl groups, markers of advanced photooxidation. The presence of these functional groups in the treated polymer confirms successful degradation. The breakdown continues to yield volatile compounds such as ethane and formaldehyde, which can eventually be fully oxidized to carbon dioxide and water.

Despite their advantages, using nanocatalysts in the form of dispersed powders poses several practical challenges, particularly concerning their recovery and reuse. These issues are critical, as there is a potential risk of nanoparticle release into the environment. To address these concerns, researchers have explored various strategies to immobilize the catalysts onto solid supports such as glass beads, fibres, silica, stainless steel, and textiles, or by embedding them within polymer matrices [86,100]. Figure 8 illustrates the various types of nanophotocatalysts used for MP removal, while Table 4 present their operational conditions and corresponding removal efficiencies for different types of MPs.

Nanoparticle-based membranes and membrane processes: Membranes function as selective barriers that permit the passage of specific substances, while blocking others. Based on pore size, membranes are generally classified into four main categories: ultrafiltration (UF), microfiltration (MF), reverse osmosis (RO), and nanofiltration (NF). MF membranes typically remove particles between 0.08 and 2 µm, UF targets those in

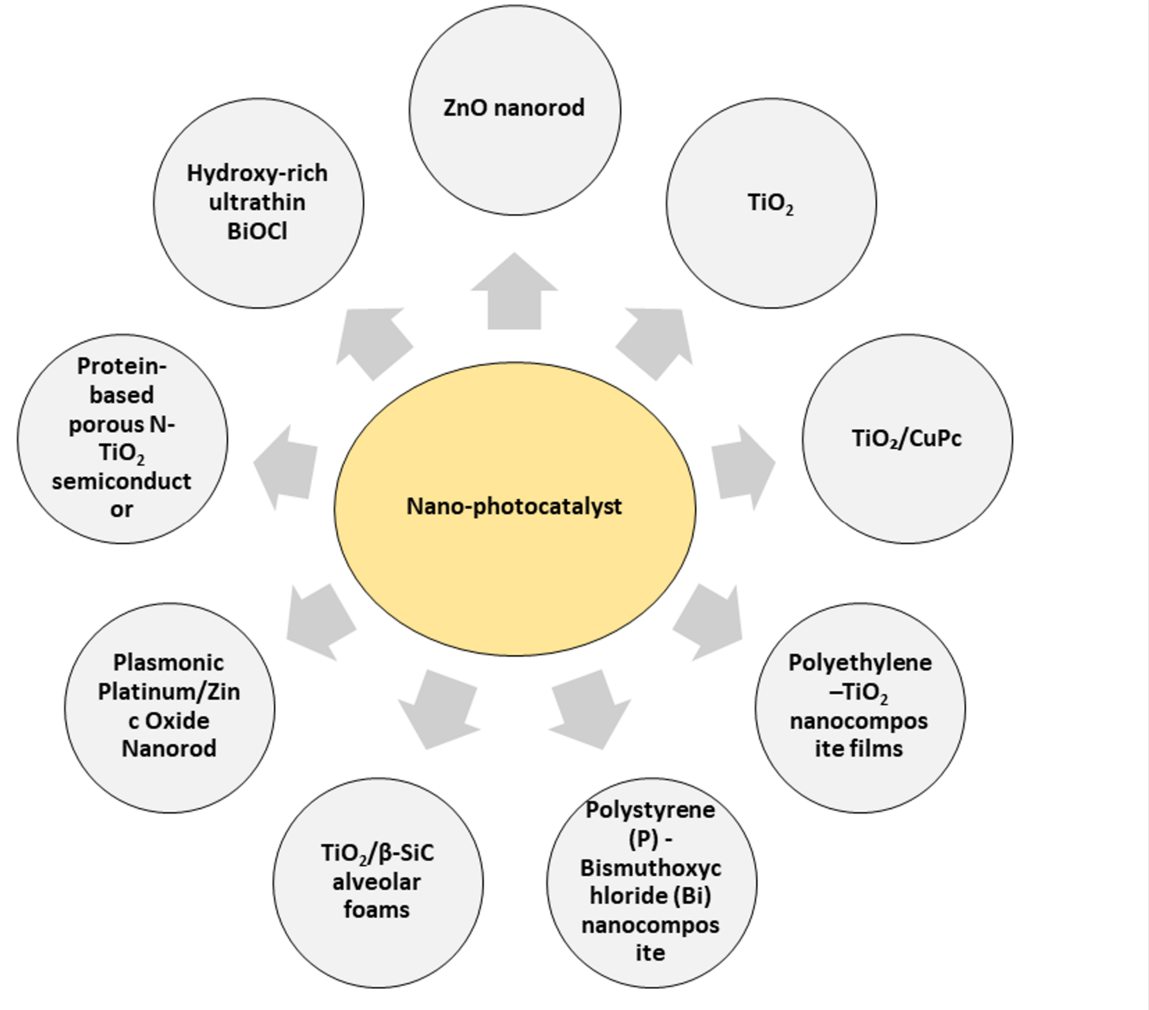

Figure 8: Different types of nano-photocatalysts used for the treatment of MPs.

Table 4: Nano-photocatalysts used for MP removal.

Photocatalyst	MPs	Condition	Findings	Ref.
ZnO nanorods (ZnO NRs)	PP	Photocatalytic treatment was performed under visible light provided by a 120 W tungsten-halogen lamp (ES-HALOGEN), delivering an intensity of approximately 0.6 SUN (60 mW/cm^2), as measured at 20 cm distance with a power meter.	65% reduction in average particle volume	[101]
TiO_2 (Degussa P25)	PP	The photocatalytic degradation experiments were conducted inside a UV chamber equipped with a 75 Watt ultraviolet lamp, which emitted light primarily at a wavelength of 254 nm. During the tests, each sample was positioned 25 cm from the UV source and subjected to irradiation for durations of 100 and 500 hours. Throughout the exposure period, the chamber temperature was consistently maintained at 40 °C.	Degradation confirmed through increased carbonyl peak intensity and morphological changes	[102]
TiO_2/CuPc (copper phthalocyanine-sensitized titanium dioxide)	PS	PS-TiO_2 and PS-(TiO_2/CuPc) films were irradiated under three 8 W fluorescent lamps (310–750 nm), total light intensity 1.75 mW/cm^2 (UV portion ≈0.05 mW/cm^2), at 7 cm distance. The setup was in ambient air at ≈298 K in a sealed lamp box (30 × 25 × 15 cm).	Enhanced degradation efficiency compared to pure TiO_2: higher PS weight loss rate, lower average molecular weight, reduced volatile organic compounds, and increased CO_2 production. ROS generated on the catalyst surface play a crucial role in chain scission	[103]
titanium dioxide (TiO_2)	HDPE	HDPE was blended with 3 wt % TiO_2 using a torque rheogoniometer at 150 °C, 60 rpm for 10 min. UV irradiation was performed using a xenon lamp (0.51 W/m^2 at 340 nm, 65 °C, 25 cm distance) for up to 400 hours	The HDPE/TiO_2 composites maintained high solar reflectance after UV irradiation. The solar reflectance after UV exposure depended on changes in crystallinity, surface roughness, and the structure of TiO_2. Anatase TiO_2 particles slightly increased solar reflectance in the near-infrared region post-UV irradiation, suggesting a potential approach to achieve high reflectance in polymeric materials. Temperature tests confirmed that the cooling performance correlated with solar reflectance measurements.	[104]
TiO_2 nanoparticles	PEF	The UV-induced degradation of polyethylene (PE)–TiO_2 composite films was conducted in a custom-built chamber equipped with two 15 W ultraviolet lamps emitting at 365 nm. The films were placed 20 cm from the light source inside a lamp housing box (dimensions: 55 cm × 35 cm × 30 cm), and continuously exposed to UV light for a duration of 300 hours	TiO_2 showed better photocatalytic property under UV radiation which showed weight loss up to 18% in 300 h compared to commercially available TiO_2	[105]
polyethylene–TiO_2 nanocomposite films	PEF	The solar degradation experiments were conducted by placing three sets of film samples in petri dishes and exposing them to natural sunlight during summer months, daily from 9:00 a.m. to 4:00 p.m., under light intensities ranging between 75,000 and 95,000 lux.	When exposed to solar radiation, the composite films showed a significant weight loss of 68% within a period of 200 h	[106]
novel photodegradable low-density polyethylene–TiO_2 nanocomposite film	LDPE	The films were placed in quartz vessels and were irradiated under a 30 W ultraviolet lamp with a primary wavelength of 254 nm. Each sample was weighed every 48 h by an accurate balance	After 400 hours of UV light exposure, the composite film exhibited a weight reduction of 68.38%, along with significant declines in molecular parameters – showing a 94.56% decrease in the weight-average molecular weight (M_w) and a 93.75% decrease in the number-average molecular weight (M_n).	[107]

Table 4: Nano-photocatalysts used for MP removal. (continued)

polystyrene (P) - bismuthoxychloride (Bi) nanocomposite films	PS	The photo-oxidation reaction of neat PS and P/Bi composite samples performed under 500 W Halogen luminaire lamp, where the temperature during irradiation was maintained around 298 K. The light intensity is measured to be 15 × 103 lx at 5 cm away from the lamp. Size of the film sample was about 78 cm^2.	The outcomes acquired the surfaces of as-prepared polymer films with BiOCl were effectively degraded by photooxidation reactions.	[108]
TiO_2/β-SiC alveolar foams	PMA and PS NPs	Three TiO_2–P25/β-SiC foam monoliths were placed inside a tubular quartz reactor. Each foam sample (10 g) contains 10 ± 1 wt % of TiO_2. The reactor was externally surrounded by four UV-A lamps (Philips T5 15W/10 Actinic BL, λ_{max} = 354 nm), positioned at a 1 cm distance from the quartz wall. Each lamp emitted approximately 4.5 mW/cm^2 at the reactor surface.	about 50% of the carbon of polymethylmethacrylate nanobeads is degraded in 7 h	[108]
plasmonic platinum/zinc oxide nanorod	LDPE	The photocatalytic degradation studies of ZnO and ZnO-Pt substrates were carried out using a 50 W dichroic halogen lamp in ambient air, providing visible light illumination with an intensity of approximately 60–70 × 10^3 lx at a distance of 10 cm from the samples. The photocatalysis of low-density polyethylene film samples (size: 1 cm × 1 cm) was performed for 175 hours in a Petri dish containing the synthesized catalysts and deionized water under the same illumination conditions.	The plasmon-enhanced ZnO-Pt photocatalyst demonstrated effective degradation of microplastic contaminants, specifically residual low-density polyethylene (LDPE) films in water. Compared to unmodified ZnO nano rods, the ZnO-Pt composite exhibited approximately 13% greater efficiency in facilitating the oxidative degradation of LDPE films.	[109]
protein-based porous N–TiO_2 semiconductor	HDPE	Photocatalytic experiments using the control sample, sol–gel synthesized N–TiO_2, were conducted by introducing 200 mg of isolated MPs along with 100 mL of distilled water into a batch reactor coated with N–TiO_2. All photocatalytic reactions were carried out within a sealed chamber at ambient temperature. The system was exposed to visible light emitted by a 27 W fluorescent lamp, positioned 120 mm away from the samples, for a continuous duration of 20 hours.	Photocatalytic degradation of the HDPE/N-TiO_2 composite in water at room temperature showed no measurable mass loss in the absence of light exposure. However, under visible light irradiation, the system exhibited progressive degradation for the initial 18 hours, after which the reaction plateaued. The total mass loss was determined to be 6.40%, with a reaction rate approximately three times higher than that observed in the solid-state photocatalytic setup.	[110]
hydroxy-rich ultrathin BiOCl	PE	Microplastic degradation experiments were performed using a circulating water system illuminated by a 250 W xenon lamp. In each test, 1 g/L of micron-sized polyethylene (PE-S) or 10 g/L of millimeter-scale plastics such as HDPE, PP-W, PP-B, PP-R, PA66, or POM was suspended in 100 mL of water. Subsequently, photocatalyst was introduced at a concentration of 1 g/L. Following a 5 hour irradiation period, the lamp was switched off, and the reaction mixture was filtered using a 300 mesh stainless steel screen to separate the plastic residues from the solution.	BiOCl-X exhibited significantly enhanced photocatalytic performance in microplastic degradation, with the resulting mass loss being 24 times greater than that achieved using conventional BiOCl nanosheets.	[111]

[a]PE – polyethylene, PS – polystyrene, HDPE – high density polyethylene, LDPE – low density polyethylene, PMA – polymethylmethacrylate, PS NPs – polystyrene nanoplastics, PEF – polyethylene film, POM – polyoxymethylene.

the 0.005–0.02 µm range, and NF membranes capture particles around 0.002 µm. RO membranes, in contrast, are widely applied in desalination processes for treating seawater and brackish water [111]. The physical mechanisms involved in the removal of pollutants are schematically represented in Figure 9 and explained in Table 5 [112].

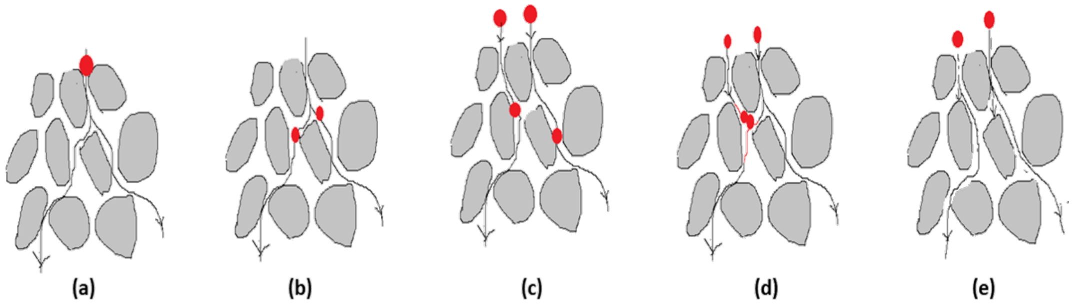

Figure 9: Physical mechanism of MP removal (a) mechanical straining, (b) sedimentation, (c) interception, (d) flocculation, and (e) impaction.

Table 5: Physical mechanism of pollutant removal.

Mechanism	Description
mechanical screening	MPs larger than membrane pores are physically blocked
sedimentation	heavier plastic particles settle near the membrane surface or within membrane modules due to gravity or flow velocity changes
flocculation	coagulated or bio-aggregated MPs clump together and form larger aggregates, making them easier to retain
interception	particles following water flow lines come into contact with membrane surface and are trapped, even if smaller than pore size
impaction	MPs deviate from water streamlines due to inertia and collide with the membrane surface or embedded nanoparticles

Membrane technology faces a key limitation in balancing selectivity with permeability, often resulting in a compromise between the two. High energy demands further restrict the widespread adoption of pressure-driven membrane systems. Additionally, membrane fouling not only raises energy consumption but also adds complexity to system operation and design. This fouling also shortens the operational lifespan of membranes and their associated modules. The efficiency of a membrane system is primarily governed by the material used in its construction. Enhancing membranes with functional nanomaterials provides a promising path to boost permeability, reduce fouling, and increase both mechanical and thermal durability, while also enabling advanced capabilities such as self-cleaning and pollutant breakdown [113]. Recently, the utilization of nanomaterials has gained significant attention for creating next-generation membranes with enhanced anti-fouling and anti-scaling, and improved transport capabilities. Among the most frequently used nanomaterials in membrane fabrication are zeolites, various metals and metal oxides, as well as carbon-based materials such as CNTs and graphene derivatives [86]. The nanomaterials that can be used membrane components for the removal of MPs are discussed in detail below.

Metal-organic frameworks: Metal-organic frameworks (MOFs) are a complex and relatively new category of highly porous nanomaterials that have gained attention over the past two decades, showing broad potential in wastewater treatment. These crystalline materials are formed through coordination bonds that connect clusters or metal ions with multidentate or bidentate organic ligands. Sometimes MOFs are referred to as porous coordination polymers. MOFs are created by combining clusters or metallic ions with inorganic or organic ligands. The metallic component consists of metal ions or clusters with organic or inorganic ligands like sulfonate, phosphonate, carboxylates, and heterocyclic compounds [114]. MOFs possess a combination of properties including as low density, large porous structure, and high adsorption capacity, which makes them suitable for wastewater treatment [115]. In addition, the strong coordination bonding within their framework results in a large specific surface area, which in turn offers the potential to control membrane pore size and enhance the removal efficiency of nanoparticles and MPs. Membranes developed using MOF-based nanomaterials offer scalable control over surface charge and pore size, enabling high separation efficiency along with favourable thermodynamic properties. Although extensive studies have been conducted regarding MOF-modified membranes for the removal of salts and organic dyes, their application in microplastic removal remains largely unexplored. Because of their excellent compatibility, highly porous structure, and adjustable pore dimensions, designing a durable and compact MOF nanocomposite membrane could provide an effective strategy for MP filtration [116]. The mechanism involved in the removal of MPs using MOFs is represented in Figure 10.

Gnanasekaran et al. [117] developed a novel composite membrane by integrating sustainably synthesized MIL-100 (Fe) MOF nanoparticles into a polysulfone (PSF) matrix. This PSF/MIL-100 (Fe) membrane exhibited substantial improvements over the unmodified PSF membrane (M0), particularly in terms of membrane structure, surface hydrophilicity (with the water contact angle decreasing from 84.6° ± 1° to 64.2° ± 1.2°), work of adhesion, wetting energy, porosity, and pore dimensions. Among various loadings, the membrane with 0.5 wt % MIL-100 (Fe) (M0.5) showed the best overall performance. It delivered a pure water flux over ten times higher than M0 and achieved over 99% removal efficiency for methylene blue (MB). Additionally, M0.5 demonstrated excellent resistance to fouling when filtering MB dye and microplastic mixtures. The membrane maintained its high performance across different MB concentrations, MPs levels, and transmembrane pressures. The study concludes that PSF/MIL-100 (Fe) composite membrane offers a promising solution for the removal of MPs [117].

Chen et al. [118] developed a series of zirconium-based MOF foam materials with interconnected pores, excellent stability, and high structural uniformity for the removal of MPs from both seawater and freshwater. These materials proved effective across a wide range of MP concentrations and types. Among them, UiO-66-OH@MF-3 demonstrated the highest efficiency, achieving MP removal rates of up to 95.5% ± 1.2%, while maintaining consistent performance across multiple reuse cycles and large-scale filtration tests. Additionally, a lab-scale automatic filtration system powered by solar energy was designed and implemented, showcasing the feasibility of integrating these high-performance foam materials into sustainable filtration technologies. This combined approach offers promising potential for advancing innovative solutions in MPs remediation.

You et al. [119] synthesized a robust composite material, ZIF-8@Aerogel, by growing Zn-based MOF ZIF-8 directly onto wood-derived aerogel fibres. This composite demonstrated effective MP removal in both freshwater and seawater simulations. Specifically, it achieved a removal of 85.8% for polystyrene particles (90–140 nm) and 91.4% for poly(1,1-difluoroethylene) particles (60–110 nm). These findings highlight the potential of this material as a promising approach for eliminating small scale MPs from environmental water sources.

MXenes and metal oxides: MXenes, two-dimensional nanomaterials, have received interest across scientific fields owing to their exceptional chemical and thermal stability. Their chemical formula is $M_{n+1}X_nT_x$ (n = 1, 2, or 3), where M denotes an early transition metal such as titanium, molybdenum, or vanadium, while X denotes carbon and nitrogen, and T_x represents surface functional groups like oxygen, fluorine, hydroxy, or hydrogen. MXenes are synthesized by selective removal of A-layers with elements from group IIIA or IVA, such as aluminium or silicon, from a parent material. This process results in a nanomaterial with an expansive surface area and layered, folded structures. These 2D materials are known for their chemical robustness, surface functionality, hydrophilicity, excellent electrical conductivity, and eco-friendly nature. Due to these properties, MXenes, particularly titanium carbide derivatives ($Ti_3C_2T_x$), have become widely explored for applications such as water treatment and purification [114].

Yang et al. [120] introduced for the first time a membrane with an enhanced water permeability. This membrane was obtained

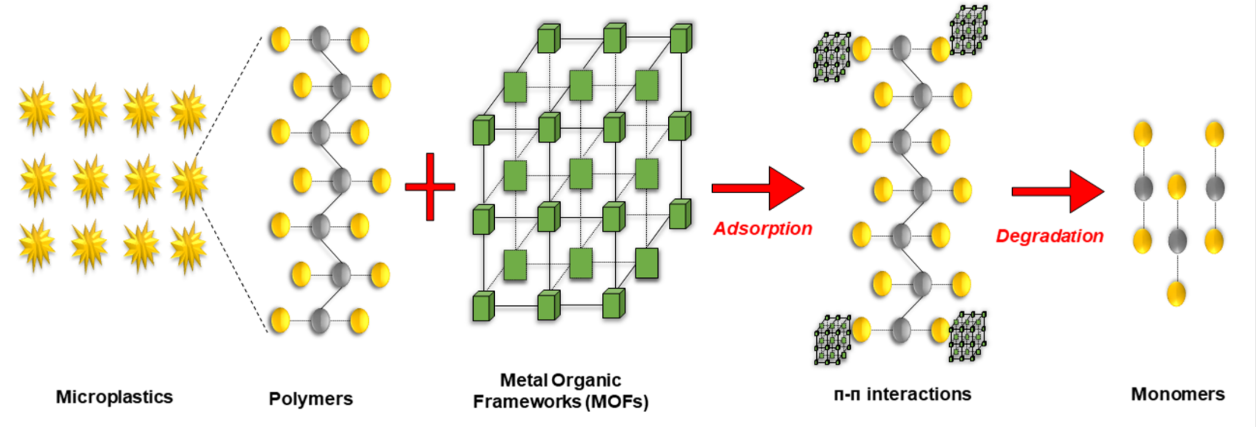

Figure 10: Mechanism of MP removal using MOF.

by selectively etching Co_3O_4 nanoparticles embedded within $Ti_3C_2T_x$ nanosheets, followed by vacuum filtration. The resulting h-$Ti_3C_2T_x$ nanosheets possess a porous, flat structure with 25 nm diameter holes ideal for MP separation. When tested with fluorescent polystyrene (FP) microspheres of varying sizes as MPs models, the membranes demonstrated exceptional removal efficiency of up to 99.3%. Additionally, a high water flux of 196.7 $L \cdot h^{-1} \cdot m^{-2} \cdot kPa^{-1}$ was recorded, surpassing or matching the performance of most membranes fabricated from unmodified two-dimensional nanomaterials. The material exhibits physicochemical stability, excellent permeability, and superior MP removal capabilities; hence, h-$Ti_3C_2T_x$ membranes show strong promise for practical use in filtering MPs and other suspended particles from wastewater.

Urso et al. [121] introduced a novel method for real-time capture and detection of NPs in a three-dimensional environment using multifunctional microrobots derived from MXene-based oxides. The fabrication process involves thermally transforming $Ti_3C_2T_x$ MXene into multilayered TiO_2 with photocatalytic properties, followed by coating with platinum and decorating the surface with magnetic γ-Fe_2O_3 nanoparticles. These engineered γ-Fe_2O_3/Pt/TiO_2 microrobots exhibit light-driven, fuel-free movement with six degrees of freedom due to their negative photogravitaxis. Their self-propelling capability, combined with tunable surface charge (zeta potential), enables rapid attraction and capture of nanoplastics onto their surfaces and between layered structures. The magnetic nature of the microrobots allows for easy retrieval. Acting as mobile platforms for preconcentration, these microrobots facilitate the electrochemical sensing of nanoplastics using inexpensive, portable electrodes. This proof-of-concept offers promising potential for real-time, on-site detection and subsequent removal of nanoplastics from aquatic systems.

MXenes have emerged as promising materials for antibacterial applications and have shown strong potential for the use in water purification membranes due to their excellent film-forming ability and enhanced mechanical strength. These properties also support their application in creating selective membranes for water desalination. Despite these advantages, the use of MXenes in certain areas remain limited. Their ultrathin 2D structure can present challenges, including unpredictable pore distribution and a tendency to collapse [122]. As a result, further research is necessary to fully explore and optimize MXenes' capabilities, particularly for the removal of MPs from water. The mechanism involved in the removal of MPs using MXenes is shown in Figure 11.

To develop lasting strategies for combating water pollution, integrating metals and metal oxides into membrane systems has emerged as a promising approach. Materials such as silver, ZnO, TiO_2, and iron oxide are frequently used in membrane construction due to their high reactivity and effective catalytic behaviour. These membranes are not only simple to engineer but also exhibit strong antibacterial activity. Additionally, their ability to trigger photocatalytic reactions under UV light makes them effective for breaking down MPs. Among these materials, silver is especially valued for its suitability in creating corrosion-resistant surfaces. Membranes composed of metals and metal oxides exhibit strong adsorption capabilities due to electrostatic interactions, making them highly effective in capturing

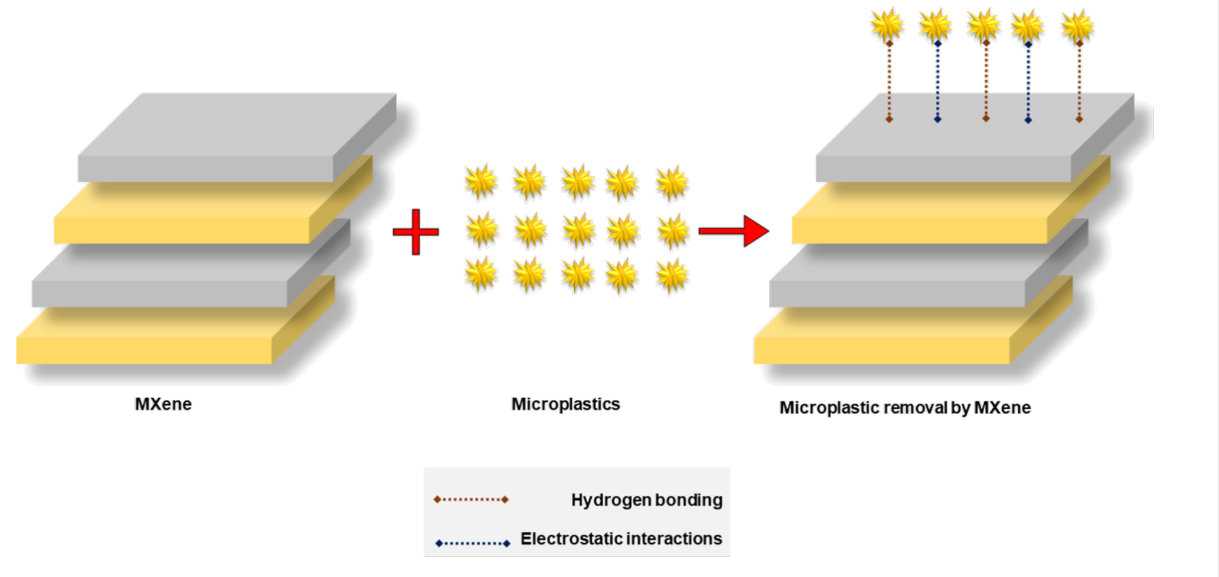

Figure 11: Removal mechanism of MPs using MXene.

MPs. Their fast adsorption kinetics support rapid water purification, and surface modifications can further enhance their performance and selectivity. These membranes are also versatile and applicable in various treatment scenarios. However, potential drawbacks include the leaching of toxic metal ions or nanoparticles, which may pose environmental and health concerns. Over time, fouling and clogging caused by MPs and other pollutants can reduce their operational efficiency, necessitating regular cleaning. Moreover, high production costs limit their practicality for widespread use in large-scale water treatment facilities [114].

Zeolite and carbon nanomaterials: Research has shown that zeolite membranes can retain both their adsorption capability and structural stability across a range of environmental conditions, making them suitable for long-term applications in water treatment. Although zeolites have not yet been widely employed in membrane form specifically for microplastic removal, their highly porous structure provides a strong ability to capture MPs from water. Their design can be tailored to selectively adsorb different types of MPs depending on factors such as charge, size, and chemical composition. Being naturally abundant and environmentally friendly, zeolites offer a cost-effective option for sustainable water purification. However, challenges such as cost and consistent supply of high-quality zeolites can impact their large-scale application. Additionally, their adsorption performance can decline under extreme pH conditions, necessitating pH adjustment to achieve optimal efficiency [114]. The mechanism involved in the removal of MPs using zeolite is shown in Figure 12.

Membranes enhanced with carbon-based nanomaterials present several benefits for removing MPs from water. Their exceptionally large surface area and distinct structural features contribute to effective microplastic capture. Materials like CNTs also offer excellent mechanical strength and can be engineered for durability under extreme conditions, making them reusable and cost-effective in the long run. However, the high production cost of carbon nanomaterials may hinder their adoption in large-scale water treatment systems. Environmental concerns also arise due to the potential release of these nanoparticles, which may pose risks to both human health and ecosystems. Additionally, carbon nanomaterials often aggregate in water, diminishing their adsorption efficiency, and their fabrication typically involves advanced techniques and costly equipment, which further limits widespread use [114]. The mechanism involved in the removal of MPs using each material is discussed in Table 6.

Challenges and advancements in MP detection

The elimination of MPs from water bodies is a key challenge in controlling environmental pollution. Although various technologies have been designed to address this issue, most are still undergoing experimental validation in laboratory settings. Some studies have also explored the potential of wastewater and drinking water treatment facilities in removing MPs. Meanwhile, because of the vast volume of water processed daily, a considerable quantity of MPs may escape into the natural ecosystems through treated water discharge [54].

Advanced strategies for MP mitigation demonstrate diverse mechanisms and operational advantages. Hybrid systems combining ceramic ultrafiltration membranes with photocatalytic reactors offer high removal efficiency (up to 99.9%) and reduced membrane fouling, but are limited by high costs and system complexity. Preventive approaches, such as glutenin-genipin cross-linked coatings, effectively reduce plastic shedding under harsh conditions using biodegradable materials; however, they address only source control and lack proven scalability. Imine-functionalized mesoporous magnetic silica nanoparticles, enhanced through machine learning (ML) optimization, enable dual removal of MPs and organic pollutants with

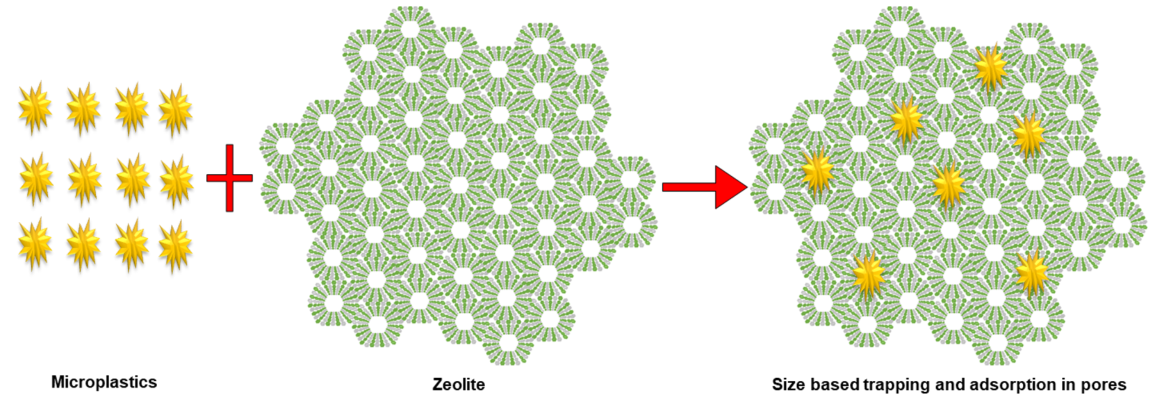

Figure 12: Removal mechanism of MPs using zeolite.

Table 6: Removal mechanism of MPs using advanced material.

Material	Removal mechanism	Examples	Reactions	Ref.
metal-organic frame-works (MOFs)	* adsorption via π–π interactions between MOF ligands and plastic surfaces (e.g.: polystyrene) * electrostatic interactions with charged nanoplastics * porous structure enables size-effective trapping and high surface area adsorption	* ZIF-8 (possess positive charge) was found to remove MPs via electrostatic attraction * through phase separation MS@ZnCo-ZIF@HDTMS sponges are used as absorber matter for MPs removal	no degradation reaction, but adsorption occurs via π–π and Coulombic interactions	[123]
MXenes and metal oxides	* electrostatic interaction between negatively charged MXene surfaces and positively charged MPs * hydrophobic/hydrophilic interactions depending on surface terminations * metal oxides (like TiO_2, Fe_3O_4) can also enable photocatalytic degradation under sunlight	* the hydrophilic nature of $Ti_3C_2T_x$ (h-$Ti_3C_2T_x$) nanosheet membranes demonstrated high efficiency in removing microplastics from wastewater * the integration of silver (Ag) metal with TiO_2 nanowires significantly improved the elimination of polypropylene microplastics.	photocatalysis: $TiO_2 + h\nu \rightarrow TiO_2\ (e^- + h^+)$ $h^+ + H_2O \rightarrow •OH$ $•OH + \text{polymer} \rightarrow CO_2 + H_2O$	[120,124]
zeolites	* ion exchange and adsorption due to high cation exchange capacity * surface electrostatic interaction enhances selective binding of charged MPs	* magnetically activated biochar-zeolite composite demonstrated a higher adsorption capacity for the removal of polystyrene microplastic	no degradation. Relies on surface polarity and ion-exchange capability	[125]
carbon-based nanomaterials	* includes graphene, carbon nanotubes, and activated carbon * hydrophobic interactions dominate between carbon surface and polymer chains * high surface area promotes multilayer adsorption	* CNTs exhibited an adsorption capacity of 1100 mg/g for polyamide, 1400 mg/g for PET, and 1600 mg/g for PE.	adsorption only	[126]

efficient magnetic recovery. Despite their potential, concerns remain regarding synthesis complexity, environmental safety of nanomaterials, and real-water applicability. These emerging methods reflect promising directions but require further validation for widespread adoption [127]. Rushdi et al. [128] developed imine-functionalized mesoporous magnetic silica nanoparticles for the simultaneous removal of polystyrene MPs and organic pollutants. The nanoparticles exhibited strong magnetic recovery and high adsorption selectivity due to imine surface groups. Machine learning was applied to optimize operational parameters, enhancing removal efficiency while minimizing sorbent use. The system demonstrated stable performance across multiple reuse cycles, highlighting its potential as a smart, dual-function remediation material [128].

Green materials are increasingly being explored for MPs mitigation due to their biodegradability and environmental safety. A genipin-cross-linked glutenin coating has shown excellent performance in reducing MPs shedding from plastic surfaces, even under harsh thermal, acidic, and saline conditions. Its self-adhesive nature, biocompatibility, and durability make it a promising preventive strategy at the source. Similarly, nanocellulose, derived from renewable biomass, exhibits a high surface area and tunable surface chemistry, making it effective for adsorbing MPs from water. Its natural abundance, low toxicity, and biodegradability position it as sustainable option for water treatment applications [129,130].

Another challenge that arises is the precise detection and characterization of MPs. Commonly employed techniques for MPs identification include spectroscopy, visual inspection, and thermal analysis. Among these, visual methods offer speed and simplicity; however, they often rely on personal judgment and are generally limited to the detection of larger particles [131].

Thermal analysis methods like thermogravimetric analysis/differential scanning calorimetry, pyrolysis gas chromatography mass spectrometry, and thermal extraction desorption gas chromatography are useful in identifying the chemical composition of MPs but are destructive analytical techniques [132,133]. Spectroscopic analysis like Raman spectroscopy often suffers from a poor signal-to-noise ratio and is affected by surface fluorescence from the samples, making careful sample preparation essential before analysis [134].

In recent years, advancements in MPs research have led to the development of innovative analytical tools for their detection, such as digital holography, scanning electron microscopy combined with energy dispersive X-ray spectroscopy, and terahertz time domain spectroscopy. These modern approaches enhance both accuracy and efficiency of detection compared to conventional methods. Nonetheless, they often involve complex sample preparation steps, which may result in cross-contamination or unintended loss of MPs particles during processing [135]. Moreover, these techniques face difficulties in accurately quantifying complex or heterogeneous samples, particularly when plastic particles are mixed with contaminants or display a typical colour [136]. While these advanced methods provide detailed and reliable data, their widespread use in large-scale and rapid environmental assessments is restricted due to their high costs, the need for careful sample preparation, and operational complexity. Conventional techniques for detecting MPs are often slow, require significant manual effort, and offer limited coverage. As a result, incorporating artificial intelligence (AI) and ML presents a promising solution by enhancing the speed, accuracy, and efficiency of MPs detection, making it a valuable tool in addressing the global challenge of MPs pollution [137].

Figure 13 provides a conceptual framework illustrating the different tools of AI and ML used in detection, classification, source identification, risk assessment, and management of MPs. Supervised learning algorithms, including linear regression, decision trees, random forests, support vector machines, k-nearest neighbours, and artificial neural networks, are widely used for predictive modelling. In contrast, unsupervised learning approaches such as k-means, spectral clustering, and mean shift are employed to identify the inherent patterns and groupings in datasets without predefined output variables, aiding in material classification or pattern recognition [138]. Hybrid and optimization based techniques including response surface methodology (RSM), particle swarm optimization (PSO), recurrent neural networks (RNN), and adaptive neuro-fuzzy inference systems (ANFIS) are useful in handling complex data types and fine tuning process parameters for improved performance [139]. Recent advancements in computational modeling and AI have significantly contributed to the de-

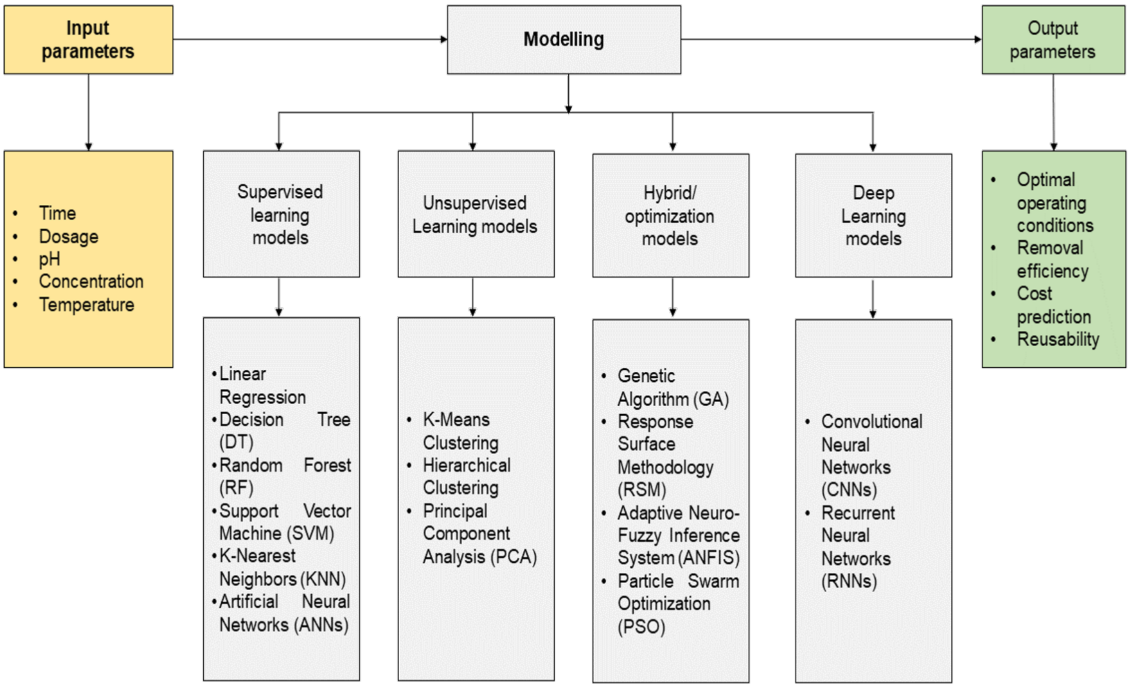

Figure 13: Different types of AI tools used for the detection of MPs.

velopment of more efficient and targeted strategies for MP and NP removal. As illustrated in Figure 13, AI and ML models serve as powerful tools for interpreting experimental data, identifying non-linear relationships among process variables, and predicting optimal treatment conditions.

Recent advancements in micro/nanorobotics have opened up new possibilities for the active removal of environmental contaminants, including MPs and NPs. These autonomous or externally guided micromachines can be engineered with functional surfaces that enable targeted adsorption, degradation, or collection of plastic particles from water bodies. For example, recent developments have demonstrated magnetically or chemically propelled microrobots capable of navigating complex aqueous environments to capture dispersed pollutants. Their high surface area-to-volume ratio, controllability, and potential for functionalization make them promising candidates for selective and efficient remediation. While still largely at the proof of concept stage, micro/nanorobotic systems represent a futuristic and highly adaptable approach to addressing micro/nanoplastic contamination [127].

In general, the future of MP detection depends on developing, with the help of AI, a standardized framework that integrates all stages, starting from data collection, to the analysis and risk evaluation. Current sampling and pre-processing methods face limitations such as complexity, inconsistent outputs, and time inefficiency, which intelligent sampling tools and cloud-based platforms aim to overcome through real-time optimization. Automated systems will enhance reagent selection and streamline workflows, increasing recovery rates during sample preparation. AI-assisted detection will combine traditional analytical techniques with ML to extract relevant features, eliminate background noise, and improve identification accuracy. In the risk assessment stage, AI will enable dynamic, real-time evaluation by integrating environmental and toxicity data, replacing outdated static methods. Ultimately, the use of AI will enhance the effectiveness of MPs monitoring and support the creation of data-driven environmental policies [134].

Conclusion

MPs have emerged as persistent and pervasive pollutants in aquatic environments, with the potential to adsorb toxic substances, persist over long durations, and bio-accumulate through trophic levels. Their widespread detection in surface water, wastewater, and even drinking water systems has raised serious concerns about ecological and public health risks. While conventional water and wastewater treatment methods provide partial mitigation, particularly for larger particles, they often fall short in effectively removing nano- and microscale plastics. This review highlighted the growing relevance of nanotechnology in enhancing MPs remediation. Nanomaterials when employed as adsorbents, photocatalysts, or membrane modifiers, offer improved surface functionality, high reactivity, and tunable interactions with target pollutants. Their integration into treatment systems has demonstrated high efficiency under laboratory conditions, particularly in improving removal performance and selectivity toward various plastic types and associated co-contaminants. However, the transition from laboratory-scale experiments to real-world implementation faces several challenges. Key among them are the scalability of nanomaterial production, energy and cost demands, potential environmental and health concerns related to nanoparticle release, and the limited performance validation in complex, real water matrices. Additionally, the absence of standardized methods for assessing MP removal efficiency, as well as the environment safety of engineered nanomaterials, continues to hinder broader adoption and regulatory development. Addressing these gaps requires a multifaceted approach.

Future research must focus on environmentally benign and scalable synthesis methods, including the use of renewable feedstocks or waste-derived precursors. The development of robust, regenerable, and multifunctional nanomaterials that balance performance with environmental safety is critical. Furthermore, combining nanotechnology with existing treatment processes and integrating renewable energy sources, such as solar-driven photocatalysis, may offer pathways toward more sustainable operation. The application of machine learning and artificial intelligence for process optimization, predictive modelling, and real-time control is also a promising area that could accelerate the design and deployment of nano-enabled systems. The establishment of regulatory frameworks and standardized protocols for toxicity testing and environmental risk assessment of nanomaterials to ensure safe deployment is also equally important. Additionally, comprehensive life cycle assessments and techno-economic evaluations are necessary to assess the environmental impact, cost-effectiveness, and feasibility of nanotechnology based systems at scale. Collectively, these strategies will help to advance nanotechnology from the research domain into practical, safe, and sustainable solutions for MPs remediation in wastewater environments.

In summary, nanotechnology holds considerable promise in addressing the complex challenge of MPs pollution. While current advancements show case high removal efficiencies and material innovations, practical deployment will require continued interdisciplinary collaboration, life-cycle assessments, and system-level integration. As global demand for clean water intensifies, nanotechnology-driven approaches, if developed responsibly and sustainably, are poised to play central role in the future of microplastic remediation.

Author Contributions

Nayanathara O Sanjeev: conceptualization; data curation; investigation; methodology; writing – original draft; writing – review & editing. Manjunath Singanodi Vallabha: writing – review & editing. Rebekah Rubidha Lisha Rabi: writing – review & editing.

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Data Availability Statement

Data sharing is not applicable as no new data was generated or analyzed in this study.

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Current status of using adsorbent nanomaterials for removing microplastics from water supply systems: a mini review

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Review

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Abstract

The widespread use of plastic has led to microplastics (MPs) being released in many water sources. MP contamination in water supply systems is a global concern due to their persistence and ability to adsorb toxic pollutants. Despite having effectiveness, conventional water treatment processes still have limited efficiency in removing MPs, especially smaller particles. Thus, it requires researchers to develop effective and sustainable strategies to deal with this matter. Many studies have shown that adsorbent nanomaterials have potential for the removal of MPs from water. This review evaluates the current status of using adsorbent nanomaterials in removing MPs from water supply systems. It discusses the occurrences and removal efficiency of MPs in water supply systems, as well as the mechanisms and performance when applying these materials for treatment. In addition, the related risk of adsorbent nanomaterials is also considered. Microplastics from land-based sources and wastewater plants persist in water supplies, with conventional treatments removing only 40–70%, especially struggling with smaller particles. Based mainly on mechanisms like electrostatic interactions, hydrophobic interactions, pore filling, hydrogen bonding, π–π stacking, and surface complexation, adsorbent nanomaterials achieve over 90% removal of MPs and can recovery. Their effectiveness depends on material properties and environmental factors, but challenges remain in scale-up and related risks. Adsorbent nanomaterials show promising potential to enhance MP removal through specific properties. Although some related risks are discussed, these materials provide a foundation for developing sustainable, effective solutions to mitigate MPs pollution in the water supply system.

Introduction

Plastic materials have become an indispensable part of modern society because of their distinct characteristics, such as low production cost, significant durability, and high flexibility. Global plastic production has risen dramatically over the past decades, reaching approximately 288 million tonnes annually, and it is projected to rise to 33,000 million tonnes by 2050 [1]. However, despite this significant increase in production, the global recycling rate remaines low at approximately 9% since 1950, resulting in the accumulation of plastic waste in ecological and environmental systems [2,3].

The issues of microplastics (MPs) related to public health and environmental risks have gained significant attention [1]. Because of their small size, high surface area, and hydrophobic properties, MPs can act as vectors for toxic chemicals, including heavy metals (lead, cadmium, or mercury) and persistent organic pollutants like polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and dichlorodiphenyltrichloroethane [4-6]. These adsorbed contaminants can bioaccumulate through the food chain and move from marine organisms to human food [7]. In water supply systems, MPs with adsorbed toxins pose significant risks without being properly removed during treatment [8]. Exposure to MPs and their adsorbed contaminants through water supply systems has been related to various adverse health effects, including endocrine disruption, neurotoxicity, carcinogenesis, and chronic exposure-related issues [9,10]. Ecologically, MPs disrupt aquatic ecosystems by interfering with feeding patterns (reduced ingestion rates), reproduction (lower egg production and fertilization success), and growth rates (lack of energy and tissue damage) in marine organisms [11,12]. Thus, the persistence of MPs threatens not only biodiversity and ecosystem stability but also human health over the long term.

These risks highlight the urgent need for effective strategies to mitigate MP pollution in both environmental and water supply systems. While numerous review papers have been conducted to evaluate the status of MP pollution, most of these papers have focused separately on sources and occurrences in the natural environment [13-15], contaminant interactions [16,17], risk assessments [18,19], extraction and analysis methods [20,21], and removal technologies of MPs [22,23] without focusing on water supply systems, which directly affect human daily life, and the potential application of adsorbent nanomaterials for MP removal. Sajid et al. provided an overview of various adsorbent materials and their efficiency [24]. However, the authors do not deeply explore the potential challenges related to large-scale applications or the integration of these materials into existing water treatment systems. Similarly, the reviews by Yu et al. and Das et al. highlighted the purification potential of different nanomaterials but lack a detailed discussion on the risks and limitations of these materials, particularly in the context of water supply systems [25,26].

To deal with current gaps, this review aims to provide aspects relating to (i) the occurrences of MPs in water supply systems and the effectiveness of MP removal throughout the treatment processes; (ii) the potential of adsorbent nanomaterials for MP removal, focusing on adsorption mechanisms and performance; and (iii) risk assessments and associated problems when applying adsorbent nanomaterials. In addition, it is important to identify critical gaps regarding large-scale applications and insufficient integration into existing systems. By expanding the scope of the research to evaluate the current status of adsorbent nanomaterials' applicability and risks for removing MPs from water supply systems, this review differs from others. Addressing these gaps is essential for developing sustainable solutions that can effectively mitigate MP pollution in water supply systems while protecting both human health and aquatic ecosystems.

Review

Sources and distribution pathways of MPs to water supply system

Microplastics can be classified as primary or secondary. Primary MPs are intentionally manufactured for various applications, whereas secondary MPs result from the degradation or breakdown of plastic waste by physical, chemical, or biological factors [27]. Figure 1 illustrates the sources and distribution of MPs from the natural environment to water supply systems. According to the study of Osman et al., land-based sources originating from plastic bags, bottles, personal care products, construction materials, clothing, sewage sludge, urban runoff, and industrial activities contribute 80–90% of MPs in water bodies [28]. The outputs from wastewater treatment plants (WWTPs) are identified as a major pathway for MP discharge into aquatic environments [29]. Data collected worldwide shows that millions of MPs are still being released. In Türkiye, a total of 6.18×10^{10} MPs from 15 WWTPs investigated were discharged into the marine environment per day [30]. A number of 4.95×10^4 to 1.49×10^8 MPs entering the environment daily was recorded in six WWTPs in Iran [31]. A study in Morocco demonstrated a significant amount of MPs discharged into the marine environment, with a daily average ranging from 1.6×10^8 MPs per day to 9.9×10^8 MPs per day in the summer [32]. Ocean-based sources, such as tourism, fishing, aquaculture, and maritime industries, account for the remaining 10–20% of MPs released into water bodies. An estimated 4622 t of MPs from commercial fishing-related activities, generated by fishing gear, nets, and ropes, are produced per year [33]. In terms of the maritime industry, the study found that new and one-year-old ropes released fewer microplastics (14–22 fragments, 11–12 $\mu g \cdot m^{-1}$) compared to two-year-old (720–247 $\mu g \cdot m^{-1}$) and ten-year-old ropes (767–1052 $\mu g \cdot m^{-1}$) [34]. Thus, natural water sources such as surface water (rivers, lakes, and streams) and groundwater have received large amounts of MPs from various sources. These water sources play

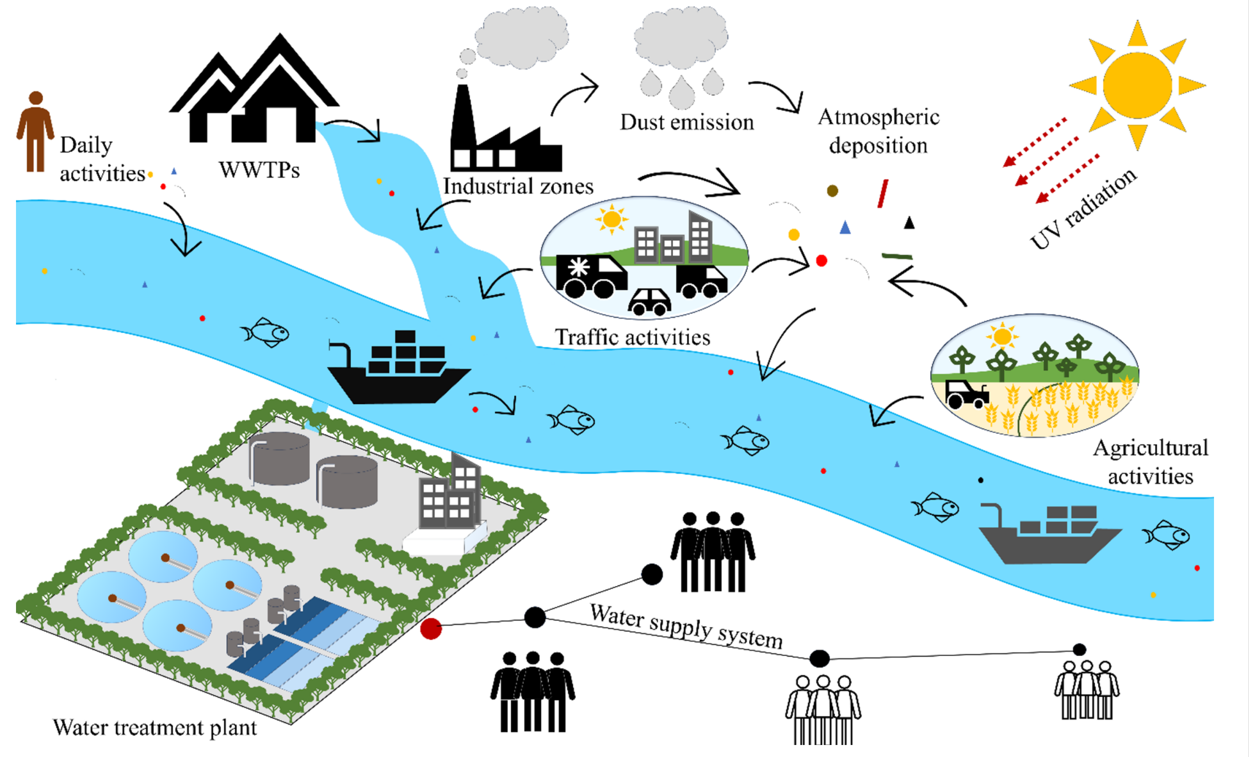

Figure 1: Sources and distribution of MPs in environmental systems.

an important role in water supply systems worldwide, and MP pollution directly affects the water quality used in water treatment plants (WTPs) [35].

The occurrences of MPs in water supply systems

The water distribution systems are responsible for transporting treated water from WTPs to various locations through the distribution pipeline network. Depending on different characteristics, including the material of pipeline, distance of transportation, analytical methods, and the size of the MPs targeted, the concentration of MPs in water will fluctuate, as shown in Table 1. Research indicated that raw water sources (rivers and lakes) often contain higher levels of MPs because of direct contact with the environment, with concentrations ranging from 1473 to 3605 particles·L^{-1}. After undergoing various treatment stages, these values decrease significantly, and MPs are still detected in treated water, with concentrations between 338 and 628 particles·L^{-1} [36]. Due to their small size and chemical stability, MPs can pass through conventional water treatment processes and infiltrate water supply systems. As reported in the study by Dalmau-Soler et al., 38% of drinking water samples from the supply network contained MPs (0.01 particles·L^{-1}). Results suggest that some particles were related to maintenance activities, while pipes and infrastructure did not significantly contribute to MP contamination [37]. Many studies have reported different results, with MP concentrations in tap water ranging from 1 to 61,000 particles·L^{-1}, in which the bulk of the data is approximately 569–751 particles·kg^{-1} [38,39]. In the study of Chu et al., MP concentrations in the water and pipe scale samples ranged from 13.2 to 134.7 particles·L^{-1} and from 569.9 to 751.7 particles·kg^{-1}, respectively, with a significantly smaller particle size in the pipe scales (50–100 µm) than in the water samples (>200 µm) [40]. In Eastern China, the level of MPs in raw water was recorded at 4960 particles·L^{-1}. After being treated by various processes, the MPs concentration significantly reduced from 4712 ± 95 particles·L^{-1} to 1012 ± 78 particles·L^{-1} [41]. Bottled water, which is normally considered safe, also contains MPs. In China, bottled water had MP levels between 13.6 and 39.3 particles·L^{-1} [42]. Research conducted in Malaysia shows that an average of 1421.20 ± 915.70 particles were found in one liter of bottled water, with most sizes below 50 µm [43]. In Bangladesh, different concentrations of MPs were found in water stored in various types of materials. The study indicated that water samples stored in glass bottles had the highest concentration of MPs (151 ± 14 particles·L^{-1}), followed by cans (134 ± 14 particles·L^{-1}), and PET bottles (95 ± 35 particles·L^{-1}) [44]. Due to the incomplete removal of MPs by WTPs and their widespread presence in water supply systems, there is an urgent need for technologies that can effectively address this issue.

Table 1: An overview of the presence of MPs in the water supply system.

Location	Sample types	MP concentration	Size	Polymer types[a]	Ref.
China	water, pipe scale	water: 13.23–134.79 particles·L^{-1}; pipe scale: 569.99–751.73 particles·kg^{-1}	water: >200 μm; pipe scale: 50–100 μm	nylon, PVC	[40]
China	tap water, pipe scale	water: 1.74–20.88 particles·L^{-1}; pipe scale: 0.03–3.48 particles·cm^{-2}	water: 21–971 μm; pipe scale: 20–2055 μm	water: PA 70.3%; pipe scale: PET 50.0%	[45]
United Kingdom	tap water; bottled water	tap: 6–100 particles·L^{-1}; bottled water: 12–62 particles·L^{-1}	tap: 32.4 μm; bottled water: 26.5 μm	PP, PE, PVC, PET	[46]
Britain	tap water	0.017–0.1513 particles·L^{-1}	>25 μm	19 polymers; PA, PET, PP, and PS commonly	[39]
China	tap water, bottled water	tap: 9.7–9.8 particles·L^{-1}; bottled water: 13.6–39.3 particles·L^{-1}	1–5000 μm	fragments, fibers	[42]
Flanders, Belgium	tap water	0.01 ± 0.02 particles·L^{-1}	25–1000 μm	PP, PET	[47]
Europe	raw water; treated water	raw water: (1473 ± 34)– (3605 ± 497) particles·L^{-1}; treated water: (338 ± 76)– (628 ± 28) particles·L^{-1}	1–5000 μm	PE, PET, PP	[36]
İstanbul, Turkey	tap water	10–390 particles·L^{-1}	12–4882 μm	EPP, NP, PE, PET, PP, PVC, PTA, VAC	[48]

[a]Ethylene propylene (EPP), neoprene (NP), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), polytetrafluoroethylene (PTA), vinyl chloride vinyl acetate copolymer (VAC), polyamide (PA), and polystyrene (PS).

Potential, classification, and comparison of adsorbent nanomaterials and other treatment methods

Adsorbent nanomaterials have recently shown great potential for removing MPs. They can be classified into four main groups, including carbon-based adsorbents, metal-organic frameworks (MOFs), magnetic nanomaterials, and aerogels and sponge-based adsorbents [49]. These materials are fabricated and modified to interact with different polymer compositions of MPs, such as polyethylene (PE), polypropylene (PP), and polystyrene (PS). The main mechanisms of MP removal depend on their structural and chemical properties, as shown in Figure 2 [50-52]. Many studies have been conducted to clarify the reaction pathways of these materials.

Classification and potential of adsorbent nanomaterials

Carbon-based adsorbents. Carbon-based adsorbents, such as graphene oxide (GO), activated carbon, biochar, and carbon nanotubes (CNTs), have been extensively investigated regarding the treatment of pollutants in general and MPs in particular. By using corncob biochar, Abdoul Magid et al. showed an adsorption of polystyrene nanoplastics (PSNPs) of about 19 mg·g^{-1}. The main mechanisms of PSNP adsorption include increased surface area from pyrolysis and oxidation, hydrophobic interactions (fresh biochar), hydrogen bonding through oxygen-containing groups (oxidized biochar), pore filling, and electrostatic interactions [53]. GO materials, such as a nickel/reduced graphene oxide (Ni/rGO) nanocomposite, also exhibited high adsorption efficiency, achieving 80.3% removal of PS from water containing 100 mg·L^{-1} PS. The primary mechanisms were hydrophobic and π–π interactions between PS microspheres and the Ni/rGO nanocomposite [54]. In addition, a mass loss of 35.66–50.46% of MP particles from aqueous polyethylene suspensions after 480 min was observed when using GO, GO-Cu_2O, GO-MnO_2, and GO-TiO_2 for treatment [55]. Recently, Yan et al. developed a reduced graphene oxide (S-rGO) membrane with small lateral size and a rejection rate of up to 99.9% while maintaining high water permeability (236.2 L·m^{-2}·h^{-1}·bar^{-1}) [56]. As another type of material belonging to carbon-based adsorbents, CNTs have also gained attention. Fabricated FeNi$_{12}$-CNTs-800 samples achieved 100% removal of PVC after 20 min of treatment, with the mechanisms attributed to the hydrophobic surface and magnetic properties of the material [57]. In a water treatment plant, by applying granular activated carbon (GAC), Arenas et al. reached 90% of MP removal, and the main mechanism involved electrostatic attractions between the positive charge of MPs and negatively charge of GAC [58].

Metal-organic frameworks. MOFs are highly ordered crystalline materials characterized by high porosity and large sur-

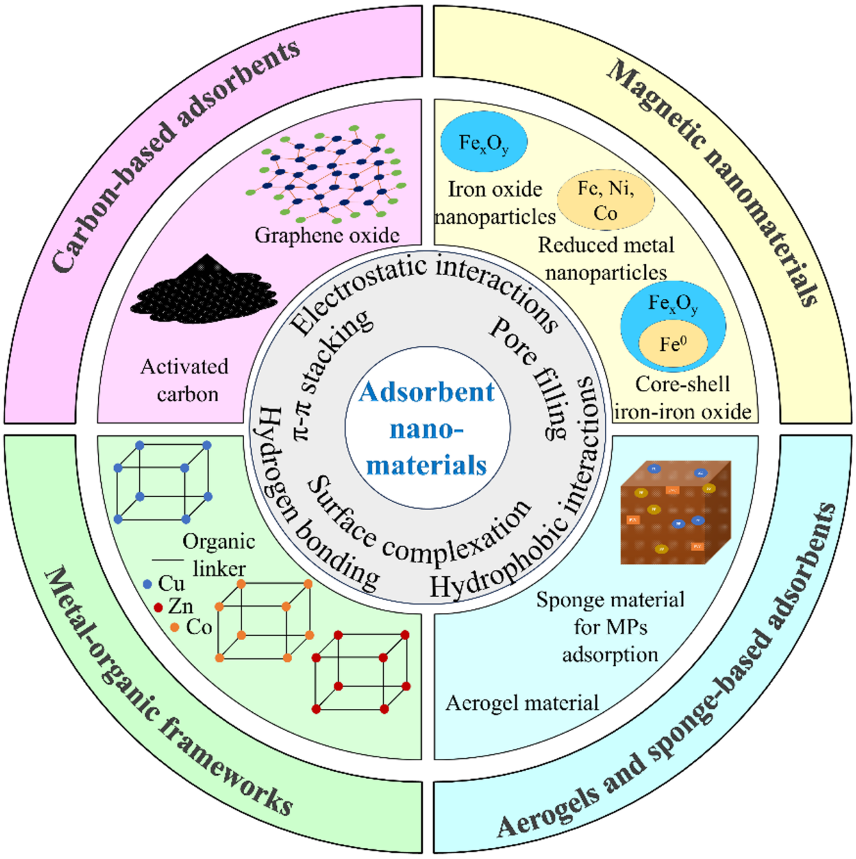

Figure 2: An illustration of the four main groups and mechanisms of adsorbent nanomaterials.

face area (Figure 3). Their pore size, volume, and functionality can be adjusted by changing the metal oxides and linkers, enabling easy synthesis and modification for diverse applications, including MP adsorption [59]. By using ZIF-8 nanocomposite, Pasanen et al. removed 99% of MPs after 1 h. The properties of nanocomposites showed highly porous structures (pore sizes of 0.3–3.4 nm) and adsorbed MPs through coordination and hydrophobic interactions [60]. Haris et al. introduced a magnetic C@FeO nanopillar adsorbent on a 2D-MOF, achieving approximately 100% removal of MPs (sizes <5 µm) after 1 h, significantly faster than conventional methods [61]. Similarly, You et al. reported on MOFs grown on a wood aerogel, ZIF-8@Aerogel, achieving removal efficiencies for polyvinylidene fluoride (PVDF) and PS particles of 91.4% and 85.8%, respectively [62]. Through electrostatic interactions, mesoporous UiO-66-NH_2/P123 exhibited exceptional performance, achieving 100% removal of MPs from suspensions with an initial concentration of 1 $g{\cdot}L^{-1}$ [63]. In the study of Modak et al., a chromium-based metal-organic framework (Cr-MOF/MIL-101) was synthesized and achieved a significant PSNP removal efficiency of 96% from suspensions with initial concentrations of 5 and 70 ppm [64]. Based on the characteristics of MOFs, a MOF-covalent organic framework (COF) hybrid membrane (FS-50/COF(MATPA)-MOF(Zr)/PDA@PVDF) was constructed and achieved an MP removal rate of approximately 100%. This hybrid membrane was evaluated as a robust and environmentally friendly material [65]. Such hybrid materials show significant ability to remove MPs and should be further investigated to improve their properties and optimize operational parameters for practical application [66].

Aerogels and sponge-based adsorbents. Porous materials, such as sponges and aerogels, can increase the number of adsorption sites for MPs/NPs, not only on the external surface but also within the internal pores, thereby enhancing the material's adsorption rate (Figure 4) [49]. Chitin–graphene oxide sponges showed an adsorption capacity of 89.8% for PS. The defined mechanisms include electrostatic attraction between oppositely charged functional groups (amino and carboxyl groups), hydrogen bonding between oxygen-containing groups and amine or carboxyl groups, and π–π stacking between GO and the aromatic rings of MPs [68]. Similarly, obtaining an MP adsorption capacity above 90.4% after three cycles, Ko et al. also confirmed that the reaction mechanisms of MPs and

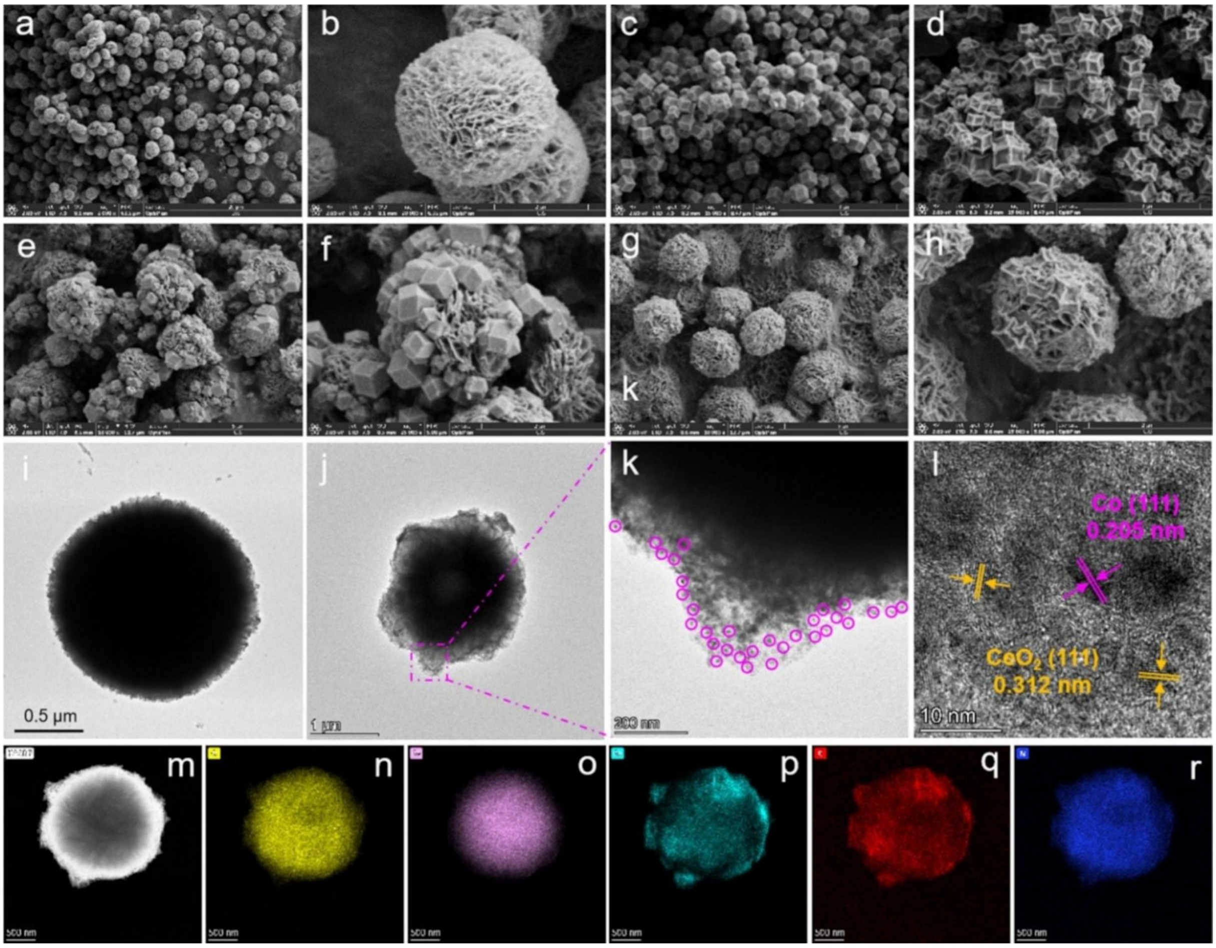

Figure 3: SEM and TEM image of synthesized Co-MOFs for removing MPs. SEM images of (a) CeO_2, (b) CeO_2 3D flower-spheres, (c, d) ZIF-67 before and after calcination at 500 °C, (e, f) ZIF-67-90@CeO_2, and (g, h) Co–N/C-90@CeO_2 composites. TEM images of (i) CeO_2 3D flower-spheres, (j) Co–N/C-90@CeO_2 composite. (k) Enlarged TEM image of Co–N/C-90@CeO_2 composite. (l) HRTEM, (m) HAADF, and (n–r) elemental mapping images of Co–N/C-90@CeO_2 composites [(n) O, (o) Co, (p) Ce, (q) C, and (r) N]. Figure 3 was reprinted from [67], *Chem. Eng. J.*, Vol. 514, by Wang, H.; Chen, H.; Wan, Q.; Zheng, Y.; Wan, Y.; Liu, X.; Song, X.; Ma, W.; Huo, P., "Catalytic degradation of polyethylene terephthalate microplastics by Co-N/C@CeO_2 composite in thermal-assisted activation PMS system: Process mechanism and toxicological analysis", Article No. 163192, Copyright (2025), with permission from Elsevier. This content is not subject to CC BY 4.0.

graphene oxide–chitosan sponges were electrostatic interactions, hydrogen bonding, and π–π interactions through Fourier-transform infrared spectroscopy and X-ray photoelectron spectroscopy measurements [69]. Integrating different types of adsorbents such as the bimetallic organic framework (ZnCo-ZIF) and sponge, MS@ZnCo-ZIF@HDTMS was successfully fabricated and demonstrated an ability to remove over 98% of MPs through electrostatic forces and hydrogen bonding [70]. By fabricating bidirectionally ordered GO–nanocellulose aerogels (D-DPGG), Liu et al. demonstrated an adsorption efficiency above 80% over 20 adsorption cycles, attributed to electrostatic attraction and hydrogen bonding [71]. Recently, an eco-friendly lily bulb-derived polysaccharide aerogel was developed, demonstrating a significant removal efficiency of 93.68% for PS. The material also maintained a stable removal efficiency of over 90% during a 3 month evaluation period [72]. Based on the conducted studies, aerogels and sponge-based adsorbents, with their high adsorption efficiency and defined mechanisms, show great promise for the removal of MPs. The continued development of hybrid materials and eco-friendly options will provide more effective solutions for the elimination of MPs and other pollutants.

Magnetic nanomaterials. To optimize the efficiency of removing MPs, magnetic nanomaterials are often integrated with physical and chemical methods during the treatment process. According to Goel et al., the physical methods primarily rely on magnetic separation, while chemical approaches focus on nanoparticle functionalization to improve their effectiveness in microplastic removal [74]. Accordingly, numerous magnetic nanomaterials have been investigated and modified to improve functionalization. To be specific, by modi-

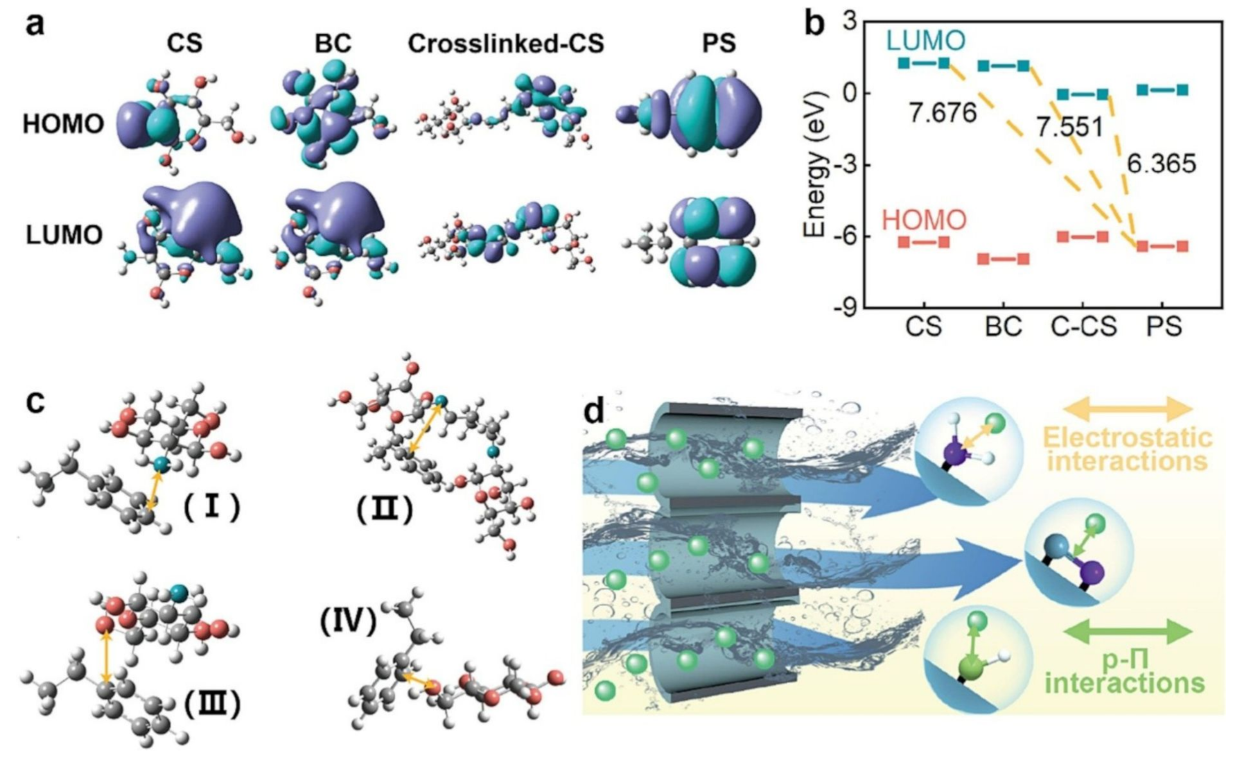

Figure 4: Illustration of (a) the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of chitosan (CS), bacterial cellulose (BC), crosslinked CS, and PS. (b) Energy gaps among PS, CS, BC, and crosslinked-CS. (c) scenarios of hardwood vessel-inspired chitosan-based sponges (BGCS)-120 adsorbing PS. (d) Schematic diagram of adsorption mechanisms. Figure 4 was reprinted from [73], *Chem. Eng. J.*, Vol. 475, by Xu, J.; Guo, Y.; Tang, C.; Qian, Y.; Guo, C.; Wang, Z.; Li, L., “Hardwood vessel-inspired chitosan-based sponge with superior compressibility, superfast adsorption and remarkable recyclability for microplastics removal in water”, Article No. 146130, Copyright (2023), with permission from Elsevier. This content is not subject to CC BY 4.0.

fying the material, Wang et al. generated magnetic biochar, Mg-modified magnetic biochar, and Zn-modified magnetic biochar with PS removal efficiencies ranging from 94.81% to 99.46%. The created materials demonstrated good reusability, maintaining performance for six cycles with only a 5% efficiency loss, and enabled in situ degradation of MPs through thermal treatment to prevent desorption risks [75]. A high capture efficiency of microplastics was also achieved using novel magnetic composite nanoparticles composed of silica, gelatin, and chitosan. At a magnetic nanoseed concentration of just 0.002 $g \cdot L^{-1}$, these composites enabled 98% PET extraction, with the separation efficiency largely influenced by the morphology of the magnetic seeds. In addition to ensuring highly efficient magnetic separation of MP particles, this approach significantly reduced the volume of synthetic flocculant sludge [76]. By applying magnetic Fe_3O_4 nanoparticles, 83.1–92.9% of MPs with particle sizes ranging from 100 to 1000 nm were removed thanks to adsorption with magnetic separation [77]. These mechanisms are influenced significantly by factors like pH, ionic strength, and MP size, with sizes below 100 µm normally requiring optimized surface functionalization for effective treatment. The influence of these factors on removal efficiency has also been highlighted in numerous studies, particularly those focusing on the synthesis of magnetic nanomaterials [52,78].

Comparison of adsorbent nanomaterials and other technologies

Water treatment processes play a crucial role in reducing MP concentrations in both water and wastewater. Conventional treatment plants, which typically employ coagulation, flocculation, sedimentation, filtration, and disinfection, can achieve a certain level of MP removal depending on the specific treatment processes and operational conditions. To be specific, when applying the coagulation/sedimentation and membrane filtration processes, the concentration of MPs decreased by about 49.6% in raw water. In a WTP, the conventional treatment process showed a removal efficiency of about 58.9–70.5% [79]. The efficiency of conventional processes is strongly affected by the size of MPs. Sedimentation has limited performance for small MPs (2–5 µm), achieving only 32.0 ± 4.5% removal [80]. Similarly, Han et al. reported a removal efficiency of 44.3 ± 3.4% using sedimentation, while Wang et al. observed 41–55% removal using Al_2SO_4 (25–32 ppm) [41,79].

Pivokonský et al. demonstrated that the coagulant type influences MP removal, with a maximum efficiency of 62% when using Al_2SO_4 [81]. Sand filtration is effective for larger MPs (>100 µm), but MPs in the range of 1–20 µm can easily pass through the filter layers, limiting the overall removal efficiency [41]. These observations highlight the persistence of MPs, especially those with small sizes, in treated water, revealing the limitations of current technologies and the need for ongoing innovation in water treatment.

Various technologies have been investigated for removing MPs, such as filtration [82], coagulation–flocculation [83], photocatalysis [84], and adsorbent nanomaterials [85]. Removal efficiencies vary widely, ranging from 47.1% for coagulation to over 90% for membrane bioreactors. Although achieving a high removal efficiency, the membrane bioreactor's performance depends on different factors, including applied material, size, and surface area [86]. Due to the varying sizes, conventional membranes are often not suitable for removing MPs that have size scale fluctuations. In addition, the high cost and problems relating to membrane fouling can affect the filtration system performance [87]. Therefore, innovative and sustainable technologies to effectively remove MPs from various environments in general, and from water supply systems in particular, are crucial to be taken into account.

In this context, adsorbent nanomaterials, which possess high surface area and modified surface properties, have emerged as a promising technology for removing MPs from water supply systems [88]. In recent years, research focus on adsorbent nanomaterials has increased significantly. The differences in MP removal efficiency between conventional processes and adsorbent nanomaterials are summarized in Table 2, providing a clear comparison of technologies, efficiencies, and recent applications. Conventional processes exhibit moderate to high efficiencies, though their performance strongly depends on polymer type and particle size. In contrast, nanomaterials show higher and more significant removal efficiency, in some cases exceeding 99%. Particularly, multifunctional materials (e.g., Fe_3O_4@PDA-lipase nanoparticles or MOFs) combine adsorption, magnetic recovery, and even catalytic degradation, indicating their potential as next-generation solutions. By using coprecipitation and thermal decomposition, Aragón et al. synthesized magnetic nanoparticles to capture PE MPs. The results demonstrated that the thermal decomposition method achieved a capture efficiency of 69.3 ± 2.1% [89]. Modifying a cellulose nanofiber aerogel, Zhuang et al. showed the ability for MP removal with an improved adsorption capacity of $146.38\ mg \cdot g^{-1}$ for MPs [90]. Thus, while conventional methods remain practical and widely applied, nanomaterial-based strategies demonstrate superior effectiveness. Despite proving efficiency, potential nanomaterial leaching raises environmental concerns, leading to the necessity for risk assessments to ensure safe integration into water treatment processes.

Risk assessment of adsorbent nanomaterials

The use of adsorbent nanomaterials has shown promise for removing MPs from aqueous environments. However, their application may raise concerns about potential hazards, and the risks associated with these nanomaterials need to be considered. Nanomaterials can pose ecotoxicological risks because of their small size, high reactivity, and potential to persist in the environment. Specifically, applying magnetic nanoparticles for treatment purposes may release toxic metal ions (Ni or Mn) or highly soluble metal ions (Zn or Mg) into the treated water, which can then enter water bodies and cause harm [74]. Similarly, MOFs, such as materials combined with Fe, Cu, or Zr, may release toxic ions into water, affecting microbial communities and bioaccumulating in food chains, as shown in the study by Yang and colleagues [110]. Carbon-based nanomaterials, like GO, have the potential to react with biological systems, causing oxidative stress in aquatic organisms by generating reactive oxygen species, leading to cellular damage [111]. According to Thirunavukkarasu et al., the interactions between these nanomaterials and other contaminants are not fully understood. While some studies suggest that different synthesis methods can reduce toxicity, they still pose a significant threat to end-users [112]. Additionally, although certain nanomaterials are designed to be biodegradable, their actual degradation strongly depends on environmental conditions. In cases of incomplete or slow biodegradation, these materials may persist and accumulate in the environment. Thus, the production and disposal of nanomaterials may generate secondary pollutants, contributing to environmental contamination [49,113].

Exposure to nanomaterials can occur through release into the environment during synthesis, application, or disposal [114]. Such exposure poses potential risks not only to human health, but also to the environment, where these materials can accumulate and interact with ecosystems, as illustrated in Figure 5. Aquatic organisms may be directly affected through water exposure, while humans can be exposed indirectly through the consumption of contaminated drinking water or seafood that has bioaccumulated these nanomaterials. Numerous adverse health effects, such as inflammation, gastrointestinal disorders, cellular toxicity, and genetic damage, are linked to nanomaterial accumulation, as shown in many studies [115]. Furthermore, the application of biosolids containing nanomaterials to agricultural soils can lead to their accumulation in the soil environment, potentially disrupting plant health and soil microbial communities, thereby affecting ecosystem sustainability [116]. Therefore, it is essential to develop safe nanomaterials and

Table 2: The effectiveness of various nanomaterials and conventional processes in removing MPs.

Treatment method	Chemical/material used	Target MP type (size)[a]	Removal efficiency	Ref.
Conventional methods				
coagulation–flocculation	$Al_2(SO_4)_3$	PS (6–90 µm)	75.6–85.2%	[91]
coagulation	polyaluminium chloride	PP, PET, PVC, PA, ABS (150 µm)	37–56%	[92]
ultrafiltration	PVDF hollow fiber membrane	PP, PET, PVC, PA, ABS (150 µm)	≈100%	
coagulation	polyaluminium chloride, ferric chloride ($FeCl_3$)	PS, PE (<500–5000 µm)	30.49–75.25%	[93]
coagulation-sedimentation	polyaluminium chloride, 1-methyl-3-propylimidazolium chloride, 1-decyl-3-methylimidazolium chloride	PS (0.1, 1, 10 µm)	≈97.2%	[94]
filtration	polycarbonate membrane, cellulose acetate membrane, polytetrafluoroethylene membrane	PA, PS (20–300 µm)	>94%	[86]
filtration	silica sand	PP, PS, PET, PVC (<10 µm)	84–98%	[95]
filtration	cellulose nanofiber-coated, delignified wood (CNF-CDW)	PS (25 µm)	95.97%	[96]
Nanomaterials				
carbon-based adsorbent	biochar-activated carbon, silica sand	PS, PA, PET (<20 µm)	81.24–96.26%	[97]
carbon-based adsorbent	banana peel biochar	PS (75–300 µm)	91.53–100%	[98]
carbon-based adsorbent	Ag-TiO_2/carbon nanotubes	PS (1.94 µm)	31.7%	[99]
carbon-based adsorbent	GO-PVA-based membrane	HDPE (125 µm)	9%	[100]
magnetic nanoparticle	Fe_3O_4@PDA-lipase nanoparticles	PET (nanometer scale)	Fe_3O_4@PDA-lipase nanoparticles magnetically remove PET micro/nanoplastics	[101]
magnetic nanoparticle	magnetic pineapple waste activated carbon	PE, PS, PET (355 µm)	86.53–89.05%	[102]
aerogels-based adsorbent	taro stem microcrystalline cellulose aerogel	PS	92.37%	[103]
aerogels-based adsorbent	TCNF/FG aerogel	PE (6–10 µm)	93.3%	[104]
aerogels-based adsorbent	CNF/PVA/r-GO/Ga radial aerogels	microplastic	99.91%	[105]
biobased hydrogel adsorbent	bamboo powder PVA	PS, PE, PVC, PA (5 µm)	92.7–99.7%	[106]
metal-organic framework	Mn-doped ZnO	LDPE	85.4%	[107]
metal-organic framework	UIO-66-EDTMP (Zr-MOFs)	PS (100 nm)	97.45%	[108]
Metal-organic framework	Fe_3O_4@carboxymethyl-cellulose (CMC) - MOFs	PS, PP, PE, PVC, PET (3 µm)	98.0%	[109]

[a] Polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), polyamide (PA), polystyrene (PS), acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polymer-like polyvinyl alcohol (PVA), ethylenediamine tetramethylene phosphonic acid (EDTMP), TEMPO-oxidized cellulose nanofibers (TCNF), flash graphene (FG).

implement effective recovery strategies to minimize the release of unexpected materials into the environment.

To manage these risks, recovery methods like magnetic separation or filtration are important to reduce residual nanomaterials in treated water. Magnetic nanoparticles can be extracted from water using magnetic separation techniques [74]. Life cycle assessments (LCAs) are critical to evaluate the environmental footprint of nanomaterial production and disposal. According to Chakrapani et al., the LCAs are conducted in accordance with ISO 14040 standards. They cover relevant aspects, including raw material extraction, nanomaterial synthesis, application in

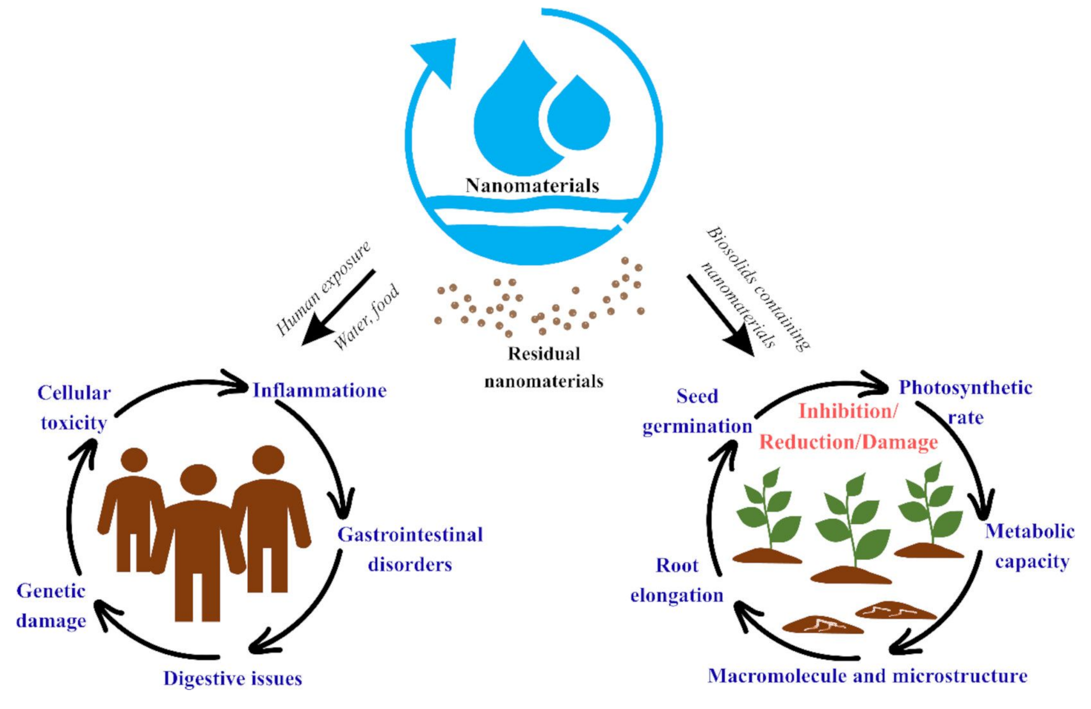

Figure 5: Adverse effects of residual nanomaterials.

water treatment, and decomposition at the end of use. The system boundaries are defined to capture the full life cycle, consisting of energy consumption, carbon emissions, and residual toxicity [113]. However, until now, in-depth LCAs conducted on nanomaterials are still relatively limited [117]. In addition, advances in anti-fouling technologies can enhance nanomaterial reusability, reducing costs and environmental impact. Although there are problems, such as the high cost of MOFs, their low stability in powder form, and the lack of standard tests for assessing nanomaterial toxicity [117]. Additionally, the long-term ecological impacts of nanomaterials remain understudied, particularly in soil environments.

Future research directions and recommendations

Future research should prioritize the development of advanced adsorbent nanomaterials that align with sustainable development goals and support a circular economy in the long term. Nanomaterials with characteristics such as environmental durability and reusability should be considered to improve overall effectiveness. Many recent studies are focusing on porous and hybrid nanomaterials to enhance the efficiency and selectivity of MP removal in water treatment processes [70,72,118]. A comprehensive understanding of the adsorption mechanisms, including surface interactions and environmental factors like pH and ionic strength, is essential to optimize these nanomaterials. Additionally, scaling laboratory findings to real-world applications remains a challenge; thus, pilot-scale studies and field trials are crucial to assess the practicality, cost-effectiveness, and environmental impact of nanomaterials in various water treatment settings. Evaluating the potential toxicity, bioaccumulation, and environmental persistence of nanomaterials is vital to ensure their safe integration into existing water treatment infrastructures [119]. Furthermore, addressing challenges such as high production costs, scalability, and the risk of secondary pollution is imperative for the widespread adoption of nanomaterial-based technologies in MP elimination [120]. Finally, along with the development of information technology, the application of artificial intelligence (AI) and machine learning (ML) can transform water treatment. Leveraging pattern detection, ML simplifies MP classification and enhances nanomaterial identification, improving research efficiency and accuracy [121]. In addition, AI can aid in designing more efficient nanomaterials (zero-dimensional to three-dimensional) and predict their performance under varying environmental conditions. Thus, with AI support, the integration of nanomaterials into current water treatment systems can be optimized [122].

Conclusion

MP pollution in water supply systems remains a pressing environmental and public health challenge because conventional treatment methods are unable to achieve complete removal, particularly for small particles. Adsorbent nanomaterials have shown strong potential for tackling this issue. Thanks to their ability to trap MPs through adsorption or magnetic separation, materials like carbon-based nanoparticles, magnetic particles, and MOFs have demonstrated removal efficiencies exceeding 90%. Their tunable properties, reusability, and potential for multifunctional performance position them as promising next-generation materials for mitigating MP contamination. However, the translation of laboratory successes to large-scale water treatment remains constrained by critical challenges, including potential nanomaterial toxicity, high production costs, limited stability, and the risk of secondary pollution. Standardized testing protocols, comprehensive LCAs, and advanced recovery strategies are urgently needed to ensure safe and sustainable deployment. Moreover, detecting and removing sub-micrometer plastics (<1 μm), which pose significant health risks due to their ability to penetrate tissues, continues to be a major obstacle. For further investigation, the development of safe, affordable, and environmentally benign nanomaterials, which are integrated with smart treatment systems, could transform current water treatment infrastructures. By combining scientific innovation with practical scalability, adsorbent nanomaterials offer a strong foundation for sustainable solutions that safeguard both human health and aquatic ecosystems.

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Conflict of Interest

No potential conflict was declared by the authors.

Author Contributions

Nguyen Thi Nhan: conceptualization; data curation; formal analysis; investigation; methodology; writing – review & editing. Tran Le Luu: conceptualization; investigation; methodology; project administration; supervision; writing – review & editing.

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Data Availability Statement

All data that supports the findings of this study is available in the published article and/or the supporting information of this article.

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Microplastic pollution in Himalayan lakes: assessment, risks, and sustainable remediation strategies

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Review

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Abstract

Microplastic contamination is a newly emerging environmental problem in the ecologically sensitive Himalayan lakes, posing a threat to biodiversity, water quality, and human habitation. These high-altitude freshwater ecosystems are being increasingly polluted through human use, tourism, glacier melt, and atmospheric deposition. Microplastic quantification in such isolated locations is, however, limited by factors such as harsh climatic conditions, logistical challenges, and the need for expert analytical techniques like microscopy and spectroscopy. The present review considers sources, pathways, and ecological impacts of microplastics in Himalayan lakes compared to other sensitive aquatic ecosystems. The review describes existing remediation technologies, categorizing these into physical, chemical, and biological interventions, and takes into account emerging sustainable approaches, including biofilm-mediated degradation and nanotechnology-based solutions. The application of nanomaterials for microplastic removal is elaborated in detail, and case studies validated their effectiveness, especially in cold environments with strong UV irradiation. In the face of increasing worldwide research into microplastic contamination, there remains a huge knowledge gap concerning its behavior in distant, elevated lake systems such as the Himalayas. The most important areas to focus with regard to the ecotoxicological impact of microplastics are the bioaccumulation of microplastics in the Himalayan food web, plasticizer toxicity, and long-term potential health and ecological threats. This review addresses the imperatives of enhanced governance, monitoring, legislation, and community-based mitigation measures. This research makes a contribution by integrating region-specific data, defining priority research needs, and provoking sustainable, multidisciplinary solutions specific to freshwater cold-climate ecosystems. This contribution serves to address the imperative of adopting multidisciplinary research, region-specific remedial measures, and judicious estimation of microplastic contamination of high-altitude lakes through by describing research gaps. It distills the present scenario and promotes novel, environmentally friendly remedial measures, regulatory policies, cooperative initiatives to combat microplastic pollution, and vulnerabilities in the fragile Himalayan freshwater aquatic ecosystems.

Review

1 Introduction

The Himalayan lakes, often known as the "Water Towers of Asia," serve an important role in biodiversity conservation, downstream hydraulic management, and supplying freshwater supplies to millions of people. Sau et al. explain that Pangong, Tsomoriri, and Tsokar are typical instances of untouched alpine lakes that support indigenous species and lifestyles [1]. The Nainital lakes, including Naini Lake and Bhimtal Lake, are crucial to the region's environment and tourism. The unique ecosystem of the lakes and rising anthropogenic pressures have made them a target for environmental research [2]. Similarly, the Ramsar wetland Loktak Lake is renowned for floating vegetation and being a sanctuary for the endangered Sangai deer [3]. These alpine lakes are exposed to increasing environmental stresses due to human population, population increase, and climate change [4]. Himalayan lakes vary widely and include, for example, the Pangong Lake (Ladakh, high-altitude, saline), the Nainital Lake (Uttarakhand, mid-altitude, urban-influenced), and the Dal Lake (Kashmir, low-altitude, densely populated). Their altitudes, catchment characteristics, and anthropogenic pressures result in distinct pathways of contamination with microplastics (MPs).

MP contamination is currently a problem of global proportions impacting freshwater, oceanic, and terrestrial ecosystems. Although initial studies primarily addressed oceanic ecosystems, current studies show the increasing load of MPs in inland water bodies, for example, rivers, lakes, and estuaries [5]. For South Asia, especially, high MP loads in major river systems such as the Ganges and Brahmaputra have all been driven by rapid urbanization, poor plastic waste management, and hydrological connectivity [6]. Yet, although the upland catchments are so crucial to maintaining these rivers, high-altitude regions, above all, the Himalayas, are still inadequately studied. Himalayan lakes are exposed to increased plastic contamination by natural and human-induced processes. The complex process of MP transport and deposition is outlined in Section 3. The harsh environmental conditions of the region, freeze–thaw weather, low microbial activity, and short hydrological retention times, make the degradation of MPs more difficult and these lakes to long-term sinks for plastic particles.

Himalayan lakes are very susceptible to MP pollution [4,7-9]. MPs enter these ecosystems due to glacier melting, tourism, agricultural runoff, and inadequate waste management. Anchar Lake and Dal Lake in Kashmir, for instance, exhibit high MP levels owing to household waste and touristic activities [10]. Recreational activities and urban runoff have resulted in plastic pollution increasing in Nainital Lake, a popular tourist destination, threatening aquatic biodiversity [2]. Nazir et al. state that MPs pollute water bodies by accumulating in food chains and bearing toxic contaminants such as heavy metals. This problem is exacerbated by the fact that plastic pollution has a transboundary implication, thereby having the chance of ending up in other lakes' sediments and water [11].

The existence of MPs in both Indus and Brahmaputra rivers suggests that the pollution from the highland lake and glacier may reach into downstream water systems [12]. According to Kumar et al., the distribution and accumulation of MP are considerably influenced by anthropogenic activities within catchment areas, which is further worsened by inadequate waste management systems. This is evident in studies conducted on lakes such as Nainital and Manasbal [2,9,13]. This review compiles recent evidence on MP contamination of Himalayan lakes and contrasts it with global high-altitude ecosystems. It will propose to identify special regional vulnerabilities, evaluate existing limitations in monitoring and remediation, and suggest strategies specific to vulnerable, cold-climate aquatic ecosystems. It tries to identify research gaps, providing practical frameworks for policymakers and researchers to protect such vulnerable ecosystems and regulate MP pollution.

2 Methodology

This is a systematic review article with the objective of consolidating the existing literature on freshwater MP pollution in Himalayan high-altitude lakes and groundwater ecosystem. Relevant literature was retrieved from ScienceDirect and Google Scholar, using the combinations of the following keywords: "microplastics", "freshwater lakes", "Himalayas", "glacial lakes", "groundwater contamination", "plastic toxicity", "MP remediation technologies", "bioremediation", "SDG 6", and "ecological risk".

Literature search was restricted to articles published in the period of 2010–2025. Peer-reviewed journal articles, book chapters, and technical reports published in the English language were included. Excluded were marine-only studies, conference abstracts, editorials, and non-peer-reviewed articles. A total of 476 records were identified. Removing duplicates and irrelevant items after title and abstract screening left 127 studies for the final synthesis. In order to facilitate transparency, a "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) flow diagram (Figure 1) is provided to describe the article selection process.

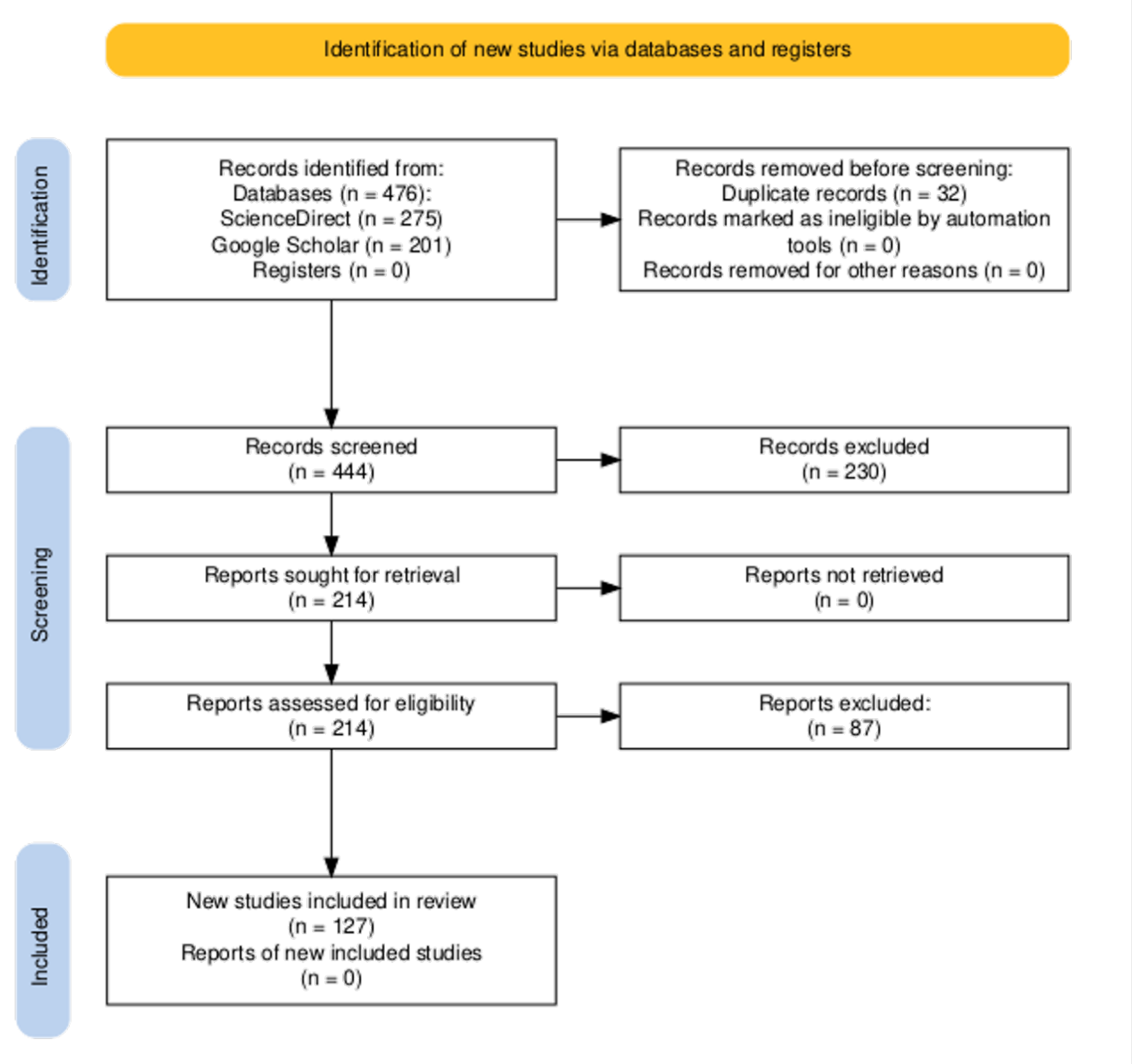

Figure 1: PRISMA flowchart of literature search and selection process [14].

3 Vulnerability of Himalayan lake ecosystems to microplastic pollution

This section presents the environmental setting and vulnerability context of Himalayan freshwater ecosystems to set the stage for the following assessment of MP pathways, effects, and mitigation measures. The Himalayan region has more than 16,000 alpine and glacial lakes, most notably being crucial reservoirs of freshwater for tens of millions of people downstream [15]. Himalayan alpine lakes are environmentally sensitive because of their glacial origin, steep altitude gradients, and high hydrological sensitivity to rapid climate change [16,17]. It is important to know the distinct environmental characteristics and sensitivities of Himalayan alpine lakes to place the mechanisms and deposition of MPs into sensitive environments in perspective [18,19].

3.1 Sources and pathways of microplastics in lakes

MPs come from various sources and are carried to high-altitude lakes in the Himalayas through several routes. The major sources of pollution are improper disposal of garbage, uncontrolled tourism, and agricultural runoff. For instance, Kashmir lakes, including Dal and Anchar, are extremely polluted due to their proximity to human dwellings and the litter that is created due to tourism [4]. Recent studies confirm the occurrence of MPs in Himalayan high-altitude lakes due to surface runoff from tourist activities, plastic trash, and unregulated effluent. For instance, Jain et al. reported a MP density of 110–370 particles/m^3 in the Nainital Lake, Uttarakhand, which was highest during the tourist season. The outcomes confirm that human accessibility and lake morphology (glacier-fed and rain-fed) influence MP density, though this interaction is poorly studied and requires further work [2]. Similar to what has been happening in Ladakh's Pangong Lake, MPs carried in the air and over long distances are deposited in water bodies via atmospheric deposition. This is a key mechanism in remote lakes besides direct input [7].

Groundwater modeling methods have been instrumental in describing the transport and fate of contaminants, including MPs, in subsurface environments. Numerical methods such as MODFLOW coupled with transport methods such as MT3DMS and RT3D are widely used to simulate groundwater flow and contaminant transport processes [20]. Such models have been adapted to cold mountain environments by adding glacier-fed recharge zones, freeze–thaw processes in soils, and topography-induced flow [21]. Semi-distributed models such as SWAT and MIKE SHE have also been used regarding Himalayan catchments to simulate subsurface flow and contaminant loading under varying climate and land use scenarios [22]. The models can be used to simulate MP transport in high-altitude lake basins, although particle-bound adaptations are under development.

The melting of glaciers has been identified as a distinct mechanism for MPs in the ecosystems of the Himalayas. MPs trapped in glacier ice are released as it melts, subsequently entering freshwater streams and lakes downstream [23]. Recently sampling in Pangong Lake and Beas catchment [2] has linked MP presence to glacial retreat zones, affirming meltwater pathways. Where Himalayan-specific data is sparse, mechanisms are inferred from analogous systems such as the Swiss Alps and Andean lakes. Seasonal MP dynamics in the Himalayan lakes are controlled by environmental factors such as glacier melting and monsoonal runoff. Summer melt pulses enhance the transport of MPs from catchment basins, whereas weak winter flows allow for sedimentation. Perennial flow of the Brahmaputra and the Koshi rivers across borders makes sure that extraneous contaminants enter such pristine ecosystems [24]. Hydrological conveyance is also seen in research in the Beas catchment, where MPs in low areas are transported upwards into sensitive ecosystems [25]. Such connectivity of the routes and sources is apparent in Figure 2, which presents the wide ecological extent and conveyance of MPs in water bodies. To allow aggregation of regional results, Table 1 reports documented MP density in

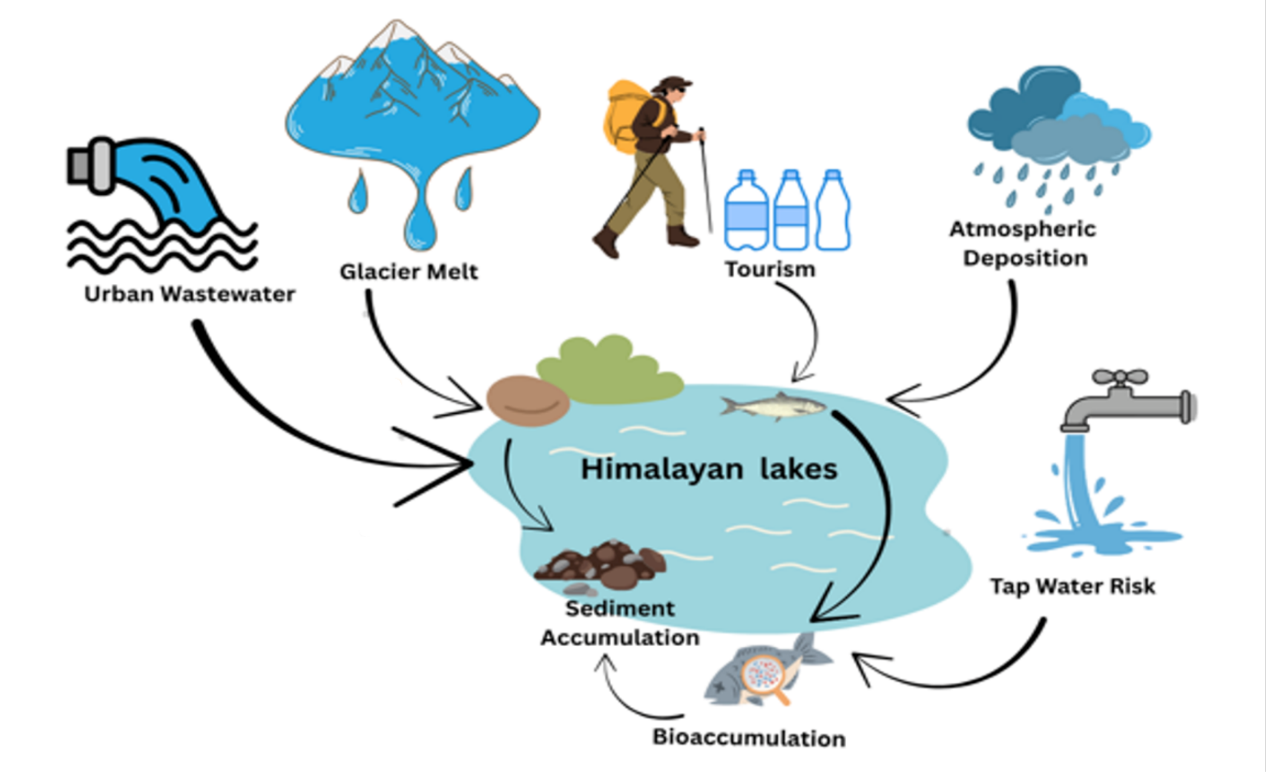

Figure 2: Infographic showing the lifecycle of MPs in Himalayan lakes. Graphical element Wastewater Vector Icon Design: © 123 Stock via Canva.com; Graphical element Melting Glacier Illustration: © Goldink Studio via Canva.com; Graphical element Hiker with Walking Sticks and Backpack: © Vanessa E. E. via Canva.com; Graphical element: Plastic Waste Blue: © Karyative via Canva.com; Graphical element Raining Cloud: © piyanuch28 via Canva.com; Graphical element Running Tap Water, Simple Illustration of Water Flowing from a Faucet: © mike223via Canva.com; Graphical element Lake element: © Visula Co via Canva.com; Graphical element Fish: © Canva Creative Studio via Canva.com; Graphical element Microplastics in Fish Illustration:© Azharialr via Canva.com; Graphical element Pile of Sediments: © Canva Creative Studio via Canva.com; Graphical element Curved thin doodle hand drawn arrow left: ©Visual Generation via Canva.com; Graphical element Curved thin doodle hand drawn arrow right: © Visual Generation via Canva.com.These elements are not subject to CC BY 4.0.

Table 1: Documented MP concentrations in Himalayan lakes.

Lake	Location	Lake type	Segment	MP concentration		Avg. MP concentration		Ref.
				Surface water [SW] (particles/m^3)	Sediment [S] (items/kg dw)	Surface water (particles/m^3)	Sediment (items/kg dw)	
Dal	Jammu and Kashmir	spring-fed	SW + S	–	–	196650 ± 350	416 ± 38	[11,26]
Manasbal	Jammu and Kashmir	spring-fed	SW + S	13000–89000	840–4020	–	–	[9]
Nainital	Uttarakhand	rain-fed	SW + S	8600–56000	400–10600	–	–	[2]
Rewalsar	Himachal Pradesh	spring-fed	SW + S	13000–238000	750–3020	–	–	[27]
Anchar	Jammu and Kashmir	river-fed	S	–	233–1533	–	660 ± 360	[10]
Renuka	Himachal Pradesh	spring-fed	SW + S	2000–64000	15–632	–	–	[28]

some Himalayan freshwater lakes and their typology. Table 2 is a compilation of the most commonly reported dominant polymers and morphologies, as well as the size classes, of MPs in Himalayan lakes.

3.2 Impact on biodiversity, water quality, and human communities

The presence of MPs in water systems significantly affects the quality of water, biodiversity, and human well-being. Studies have confirmed the ingestion of MPs by aquatic organisms, including fish, mollusks, and crustaceans in Lake Nundkol and Dal. This renders aquatic animals highly vulnerable to the action of plasticizers. Consumption of these substances interferes with metabolic processes and leads to bioaccumulation of toxic compounds, like heavy metals linked with MPs [11]. Altitude lake sediments contain high concentrations of MPs, which interfere with benthic assemblages and influence the food web structure [4]. For instance, a study in Dal Lake recorded MP concentrations of 2450 particles/m^2 in sediments and 9.8 particles/L in surface water [11], indicating significant ecological exposure.

3.3 Global comparison with other sensitive aquatic ecosystems

Across the globe, MPs have emerged as a widespread contaminant in delicate aquatic ecosystems, and Himalayan lakes exhibit numerous similarities with those found in other high-altitude or pristine environments. For example, MPs from glacial melt and atmospheric deposition cause problems for lakes in Europe’s Alpine regions, especially those in the Swiss Alps [23]. However, MPs degrade more slowly in the Himalaya’s cooler climates, which over time makes their buildup more damaging and permanent.

In South America, the Andean lakes exhibit comparable MP pathways, such as agricultural runoff and tourism, yet they vary in management approaches. According to Yang et al., systematic management methods are often not applied to the Himalayan lakes; therefore, there is a greater risk of ecological breakdown [24]. In contrast, the Andean lakes benefit from community-based rehabilitation processes. The Beas River in the Western Himalaya has been compared with rivers in temperate zones, where improved waste management systems

Table 2: Common MP characteristics including dominant polymers and morphologies, and size classes in Himalayan lakes.

Lake	Dominant polymers	Dominant morphologies	Size class (µm/mm)	Reference
Dal	PE, PS, PP, PVC	fragments, fibers, pellets	<250 µm	[26]
Manasbal	PP, PE, PS	beads	–	[9]
Nainital	HDPE	fibers	0.02–1 mm	[2]
Rewalsar	PS, PE, PP	pellets, fragments	–	[27]
Anchar	PA (96%), PET (1.4%), PS (1.4%), PVC (0.9%), PP (0.7%)	fibers (91%), fragments/films (8%), pellets (1%)	–	[10]
Renuka	PE, PS	fibers, fragments	–	[28]

cause a reduction in MP accumulation. According to Bhaduri et al., this disparity reflects how essential cooperating waste management policies and plans are in the Himalayas to prevent MP pollution [25].

Matta et al. provided a comprehensive historical analysis of water and emerging pollutants, specifically microplastics, in the Indian Himalayas, highlighting how such pollutants have progressively affected surface and groundwater as a result of unregulated use of plastic and a lack of waste management infrastructure [29]. Our research supplements theirs by emphasizing not just the presence and ecological hazards but also possible remediation technologies and SDG-consistent governance options. In addition, Nayak et al. employed pollution indices and chemometric models to assess the presence of poisonous elements in Himalayan groundwater [30]. Our addition of groundwater vulnerability modeling and toxicity pathways to this contributes by incorporating MPs into groundwater threat frameworks, providing a new contribution in linking solid plastic pollution with hydrological threats in vulnerable highland environments.

4 Methods for assessment of microplastics

4.1 Sampling strategies in remote regions

MP sampling in remote mountainous areas at high altitudes, for example, the Himalayan lakes, necessitates creative logistics and solutions adapted to environmental conditions. The conditions in these areas generally render conventional methods, for example, trawling plankton nets in surface water, infeasible owing to transport and size constraints of equipment [31]. This has given rise to sampling devices that are both portable and light, specifically tailored for use in remote environments. For example, surface MPs can be effectively collected in streams and lakes by adapting small mesh nets (100–300 µm).

The collection of sediment samples is also essential since MPs have a tendency to sink and build up over time. The most effective methods for recovering sediments from lakebeds in waters of shallow to medium depth are grab samplers and hand-held corers [32]. MP deposition greatly depends on glacial runoff and alpine seasonal tourist activities, such that seasonal sampling protocols need to be adopted. While the monsoon season in the Himalayas typically spans from June to September, this review emphasizes late-monsoon periods (August–September) due to the heightened runoff and peak tourism activity during these months. Sample collection both before and after the monsoons could potentially provide useful insight into variations in contamination levels generated due to runoff and anthropogenic activities.

The collection of both suspended and floating particulates is facilitated by the increasing use of in situ filtration systems that utilize portable vacuum compressors for water samples. These tactics aid in capturing MPs of all sizes, from the macro- to the nanoscale, which is essential for understanding the full contamination profile in remote ecosystems [33]. An overview of MP sampling and analysis methods is given in Figure 3.

4.2 Analytical techniques for microplastic characterization

4.2.1 Spectroscopy. One of the key methods of analyzing MPs is spectroscopy. Fourier-transform infrared (FTIR) spectrosco-

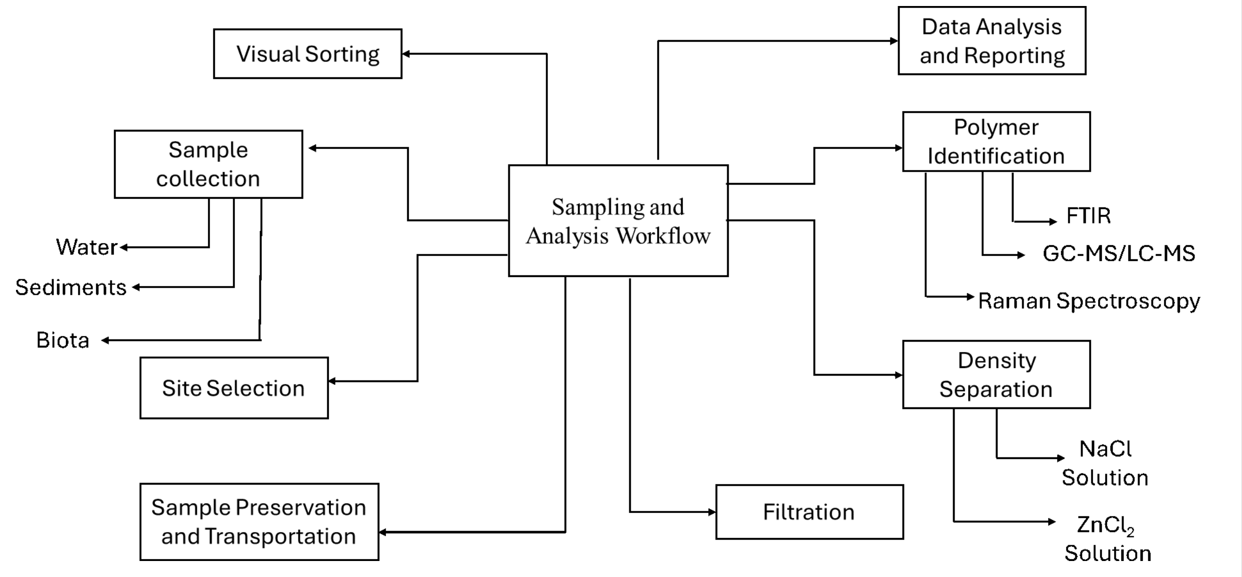

Figure 3: Sampling and analysis methods for MPs in remote regions.

py is used regularly to identify the chemical structure of MPs [34]. One of the most important developments for nanoplastic detection in complex environmental matrices is micro-FTIR to analyze particles smaller than 10 µm [35].

Raman spectroscopy improves on FTIR by using higher resolution and the ability to examine colored or pigmented polymers without dye interference. The geographical distributions of MPs in samples are increasingly being mapped using Raman mapping techniques, which provide valuable information for ecological impact studies [36]. Such techniques are able to distinguish between polymers that result from local tourist waste and those transported by atmospheric deposition in Himalayan lakes of high elevation [37].

4.2.2 Microscopy. Microscopic techniques remain crucial for the initial description of MPs, particularly when assessing their physical properties. Scanning electron microscopy (SEM) produces high-resolution images of particle shapes. It also indicates surface wear and tear patterns that reflect how old the MP is and how long it has been in the environment [38].

Ease of operation and minimal cost of optical microscopy make it widely used, despite being less sophisticated than SEM. It is particularly useful in morphological examination, size grading, and rapid particle identification. The combination of optical microscopes and modern digital imaging techniques allows for automatic particle classification and counting, which greatly decreases the extent of human intervention and possibility of error [39].

Microscopy and spectroscopy tend to be combined to increase reliability. For instance, Raman or FTIR spectroscopy is applied to identify polymers following SEM to examine the shape of particles. This ensures both chemical and physical characteristics are captured [40]. The combined analytical flow and instrumentation for MP characterization, such as digestion, preparation, and analytical processes like microscopy, spectroscopy, and thermal analysis, is presented in Figure 4.

4.3 Challenges in quantification and identification under alpine conditions

MPs assessment is particularly problematic at high altitudes, including the Himalayas. Implementation of sophisticated analysis methods and sampling is limited due to extreme climatic conditions like below-freezing temperatures, strong UV irradiation, and poor infrastructure [31]. Portable and robust field-friendly technologies are also required since it is challenging to

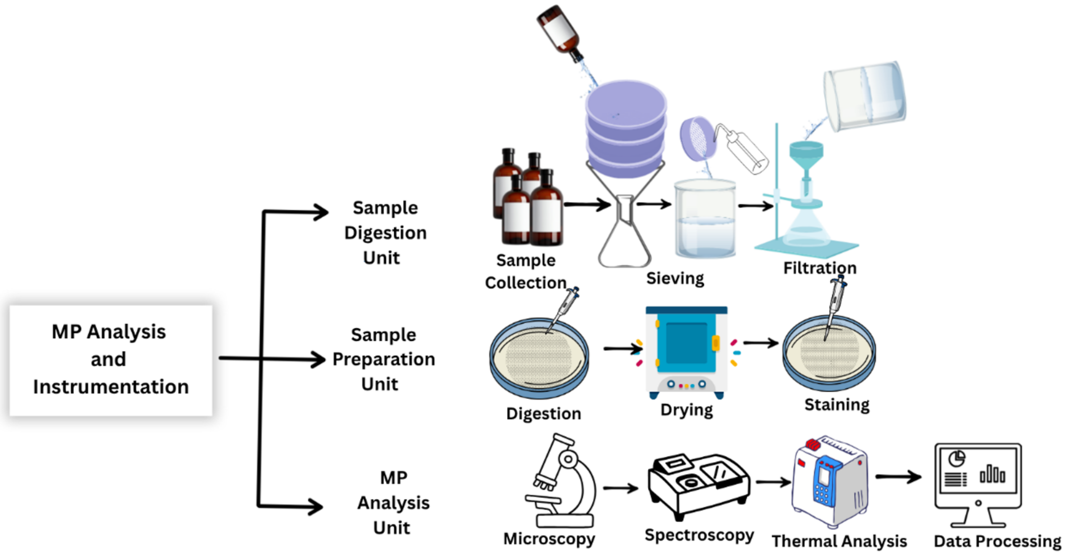

Figure 4: Diagram of MP analysis instrumentation. Graphical element Amber glass bottle with blank label: © andiiwan via Canva.com; Graphical element Laboratory Conical, Titration or Erlenmeyer Flask: © Vector tradition via Canva.com; Graphical element Filter funnel icon: © musmellow via Canva.com; Graphical element Flour Sieve Illustration: © ivandesign via Canva.com; Graphical element Splash of Water: © Billion Photos via Canva.com; Graphical element Transparent beaker with clear water on white background: © BlueRingMedia via Canva.com; Graphical element Wash Bottle: © awspicious via Canva.com; Graphical element Clean Flat Vacuum Filtration Apparatus: © sparklestroke via Canva.com; Graphical element Petri Dish with Cream-Colored Agar Illustration: © Maria Teruya's Images via Canva.Com; Graphical element Round Grid Filter Outline Thin Line Style © Serhii Borodin via Canva.com; Graphical element pipette: © heyrabbiticons via Canva.Com; Graphical element incubator: © putra-creative via Canva.com; Graphical element Microscope Outline School Supplies: © Langgeng Pangrebowo via Canva.com; Graphical element Spectrophotometer: Vectors Market via Canva.com; Graphical element Gas Chromatograph: © Aurielaki via Canva.com; Graphical element Monitor: © Ibrandify via Canva.com; Graphical element White Rectangle With Shadow: © StylishDesignStudio via Canva .com; Graphical element Triple split arrow in linear style: © Nazar12 via Canva.com; Graphical element Arrow Down Icon: © Noun Project (limited collection) via Canva.com. These elements are not subject to CC BY 4.0.

transport samples to well-equipped laboratories from distant locations.

Another challenge is that natural particulate matter such as minerals, biological debris, and glacial silt can lead to the interference of MP detection. MPs must be separated by using pretreatment techniques such as enzymatic decomposition of organic matter and density separation using saline solutions. These processes, however, might take a lot of time and could cause tiny particles to be lost [32].

The distinct combination of nanoscale dimensions and very low concentration in samples from the environment makes nanoscale plastics yet another challenge. Sophisticated methods such as thermal extraction desorption (TED) and gas chromatography-mass spectrometry (GC-MS) are now routinely used to detect these particles. But these methods involve a lot of expertise and equipment. The development of portable, low-cost systems for nanoscale analysis is a significant field of future studies [34].

5 Remediation techniques

5.1 Overview of current technologies for microplastic removal

Various physical, chemical, and biological methods are employed with the hope of effectively removing MPs from water bodies. The simplest process to remove MPs from water supplies is by physical processes. Filtration processes, including sand filtration and membrane bioreactors (MBRs), utilize size exclusion to remove MPs [41]. Tiwari et al. established that specifically MBRs have been highly efficient, with more than 99% removal efficiencies under controlled conditions [42]. Sedimentation methods are frequently used in wastewater treatment plants, making use of the density difference between MPs and water. But it is difficult to trap particles measuring less than 10 µm with such processes. Physical methods are easy to implement and scalable but lack efficiency in open, natural environments such as Himalayan lakes and often require energy-consuming setups [43]. Research also indicates that sophisticated filtering systems, including granular activated carbon (GAC) filters, effectively capture small MPs. They are therefore ideal for use in high-altitude lakes [44].

The goal of chemical methods for MP remediation is to convert polymers into non-toxic substances. Advanced oxidation processes (AOPs) use strong oxidants like ozone, hydrogen peroxide, or hydroxyl radicals to break down MPs [45]. The most promising among them are photocatalytic processes that utilize titanium dioxide nanoparticles under UV radiation. These are very efficient degradation processes for degrading plastics to carbon dioxide (CO_2) and water [43]. Fenton reactions, involving a mixture of hydrogen peroxide and iron catalysts, are a good example of a new method that has achieved great degrading effectiveness and is under study regarding its potential application to cold environments [46]. However, before being widely used in delicate ecosystems like Himalayan lakes, chemical methods must be carefully optimized since they frequently demand substantial energy input and can produce secondary pollutants [47].

Biological processes can utilize the natural ability of microorganisms to degrade synthetic polymers. Microorganisms such as *Pseudomonas* and *Bacillus*, which have enzymatic activity, can degrade plastics into smaller molecules [48]. Biofilms adhering to the plastic surfaces are required for biological degradation since they secrete enzymes that degrade polymers outside cells [49]. As noted by Rai et al., biofilms can speed up the breakdown of MPs, even though such a process is prone to interference from environmental factors like pH, temperature, and the availability of nutrients [50]. There has been promising development within the field of genetic engineering in relation to the creation of microbial consortiums optimized for high-efficiency degradation [46]. As reported by Rizvi et al., some fungi, such as *Aspergillus spp.*, have already shown potential in degrading MPs in a controlled settings, with the possibility of further application in larger-scale bioremediation schemes [44].

Table 3 gives a comparative summary of the most recent physical, chemical, and biological technologies for MP remediation. Among them are new electrochemical technologies, membrane separation technologies, microbial technologies, and AOPs. The efficiency, mechanism, strengths, weaknesses, and applications of each technology are utilized to assess each technology.

These technologies are indicative of the multidimensional strategies being pursued for MP remediation, which strike a balance between efficiency, operational feasibility, and environmental sustainability. While physical and chemical methods are dominant, the use of advanced technologies such as electrochemical systems, machine-learning-based sensing, and bioelectrochemical technology is a significant shift towards more precise and responsive MP management systems.

5.2 Potential for bioremediation in cold environments

Psychrophiles, or coldness-adapted microbes, are essential for bioremediation under the adverse conditions of high-altitude Himalayan lakes. These microbes break down polymers like PE and PS by producing enzymes that are active below freezing temperatures [69,70]. For example, it has been discovered that certain *Pseudomonas* species efficiently break down plastics in cold climates, providing a viable solution to the problem of MP contamination in alpine ecosystems [46]. Tiwari et al. found that psychrophilic lipases and esterases found in marine environments degrade MPs in low-temperature experiments, lending credibility to their use in Himalayan habitats [42]. The ecologi-

Table 3: Current technologies for MP removal.

Technology	Mechanism/type[a]		Advantages	Limitations	Efficiency	Applications	Ref.
piezocatalytic and Fenton-like H_2O_2 activation using $Bi_{12}(Bi_{0.5}Fe_{0.5})O_{19.5}$	synergistic oxidation and fragmentation of polyethylene terephthalate (PET) MPs via reactive oxygen species (ROS) generation	C	effective degradation of PET-MPs (28.9% removal in 72 h); enhanced efficiency compared to individual Fenton or piezocatalysis; durable catalyst with multiple reusability	slow degradation rate compared to adsorption or filtration methods; requires ultrasound treatment and optimized oxidant concentrations	28.9% removal for PET-MPs (10 g/L) in 72 h	industrial wastewater treatment and environmental remediation	[51]
capillary skimming using hydrophilic ratchet	capillary force-driven skimming at the air–water interface	P	effective for floating MPs (1–4 mm) with densities from 0.02 to 0.97 g/cm^3; avoids clogging issues in mesh-based filters; demonstrated feasibility with a marine robot cleaner	limited to floating MPs, ineffective for submerged or sinking MPs; dependent on water bridge stability for efficiency	high efficiency for floating MPs across different densities	marine pollution control and robotic surface-cleaning systems	[52]
settling treatment in wastewater treatment plants (WWTPs)	sedimentation based on density, size, and shape of MPs	P	effective for MPs with higher density and larger size; predictable efficiency based on settling models; commonly integrated into existing wastewater treatment processes	lower efficiency for small, low-density MPs; removal efficiency depends on surface loading rate and operational conditions	variable efficiency based on MP density, size, and shape	wastewater treatment plants and industrial effluent management	[53]
electrochemical oxidation with boron-doped diamond electrodes	indirect oxidation of MPs via reactive radicals	C	effective degradation of 1.0 µm polystyrene (PS) MPs; achieves oxidation and morphological changes in MPs; uses highly oxidizing radicals for degradation	requires optimization of power usage and electrode cost; long treatment time (5 h)	high efficiency under optimal conditions (Na_2SO_4 0.02 M, 60 A/m^2, 5 h)	advanced water treatment for MP-contaminated water	[54]
electrocoagulation (EC) using Fe and Al electrodes	coagulation and flocculation of MPs through electrochemical reactions	C	achieves 100% removal under optimal conditions; effective at pH 10 with 30 A/m^2 current density; suitable for industrial wastewater treatment	performance dependent on current density and pH; requires optimization for large-scale applications	100% MP removal at pH 10, 30 A/m^2 in 60 min	textile industry wastewater treatment	[55]
electrochemical technologies (EC, electro-adsorption, electro-oxidation, electro-reduction)	various electrochemical reactions for detection and removal of MP/NPs	C	multiple electrochemical methods available for both detection and removal; environmentally friendly and controllable; high removal efficiency depending on method and parameters	performance depends on electrode materials and operational conditions; requires further optimization for large-scale applications	high efficiency depending on technique (e.g., EC, electro-oxidation)	laboratory detection and industrial water treatment	[56]

Table 3: Current technologies for MP removal. (continued)

microbial electrolysis cells for MPs/NP removal	biofilm-based microbial electrochemical degradation and energy recovery	B	simultaneous wastewater treatment and energy recovery; potential defense mechanism via EPS secretion; novel approach for NP degradation	high concentrations of NPs (≥500 µg/L) negatively impact microbial communities; reduced efficiency due to biofilm disruption	≈43% reduction in current density and ≈48% drop in hydrogen (H_2) production at 500 µg/L PsNPs	bioelectrochemical systems, wastewater treatment, and energy recovery applications	[57]
machine learning & hyperspectral imaging (SVM model)	identification and quantification of MPs in rice through spectral analysis	P	high accuracy in MP identification (>94.44%); non-destructive and rapid detection; useful for assessing MP release during packaging and transportation	limited to solid food matrices like rice; may require calibration for different food products	>94.44% accuracy in identifying MPs in packaged rice	food safety, packaging analysis, and quality control	[58]
homoporous PVDF membrane separation	filtration using homoporous poly(vinylidene fluoride) membranes with high surface porosity	P	high rejection rate (>97%) for 500 nm polystyrene MPs; excellent water flux (662 L m^{-2} h^{-1} bar^{-1}); simple and scalable membrane fabrication process	limited to MP sizes ≥500 nm; potential membrane fouling over prolonged use	>97% removal of 500 nm PS MPs	water treatment, MP separation in aquatic environments	[59]
EC with magnetic Fe_3O_4 Floc formation	coagulation and magnetic separation of MPs, with potential reuse of Fe_3O_4 in energy materials	C	high removal efficiency (98.4%) for PE MPs; magnetic separation enables easy recovery; recyclable Fe_3O_4 for lithium-ion battery applications	requires additional steps for Fe_3O_4 recycling; may involve complex treatment for photodegradation	98.4% removal efficiency for PE MPs	wastewater treatment and recycling for energy material applications	[60]
UV/H_2O_2 AOP	oxidative degradation of MP fibres using UVC irradiation and hydrogen peroxide	C	significant mass loss of MPs (52.7%) with a half-life of 45.3 h; effective surface degradation (pits, cracks); complete COD removal in 3 h	requires high doses of H_2O_2 (500 mg/L) and prolonged exposure to UVC (48 h); limited to photoactive treatment environments	52.7% MP mass loss, 15.2% MP degradation in hospital laundry wastewater	laundry wastewater treatment and MP degradation in industrial effluents	[61]
2D MOF@C@FeO nanopillared structures	adsorption and magnetic separation of MPs and dissolved pollutants	C	high removal efficiency (~100%) for MPs in 60 min; dual functionality for both solid and dissolved pollutants; reusable for up to 6 cycles with 90% efficiency	potential complexity in synthesis of 2D MOF@C@FeO structures; requires magnetic separation infrastructure	100% MP removal in 60 min 90% efficiency after 6 adsorption cycles	industrial and domestic wastewater treatment systems	[62]
SDS-assisted electrochemical advanced oxidation process (EAOP) with BDD anode	enhanced degradation of PS MPs using SDS and persulfate generation	C	1.35–2.29 times higher degradation rate compared to BDD electrolysis alone; effective alkyl-cleavage and oxidation of MPs; low surfactant cost (<0.05% of operating costs)	prolonged treatment time (72 h); requires precise SDS dosing strategy for optimal performance	significant improvement in MP degradation rate	AOPs in water treatment for MP removal	[63]

Table 3: Current technologies for MP removal. (continued)

EC and ultrafiltration (UF) combination	coagulation followed by membrane filtration for MP recovery	C P	high recovery efficiency for MPs (85%); simultaneous removal of COD (85%), TSS (97.66%), TDS (42.74%), colour (99.74%), and turbidity (99.66%); rapid treatment time (2 min)	moderate efficiency for MP recovery compared to other methods; requires specific operational conditions (pH 7.5, NaCl 8 g)	85% MP recovery, excellent pollutant removal performance	wastewater treatment in plastic packaging industries, particularly in Vietnam	[64]
interpenetrating bipolar plate electrocoagulation (IBPE) reactor	simultaneous removal of MPs and heavy metals through EC	C	high removal efficiency for MPs (97.5%) and heavy metals (95.16%); simultaneous pollutant removal; clean technology for WWTP effluent treatment	operational cost of $0.91/L may limit large-scale use; requires precise control of current density, pH, and reaction time	97.5% MP removal, 95.16% heavy metal removal	secondary effluent treatment in WWTPs	[65]
EC with aluminum anode	flocculation and charge neutralization for MP removal	C	high removal efficiency: 93.2% for PE, 91.7% for PMMA, 98.2% for CA, and 98.4% for PP; effective across a broad pH range (3–10); works better with fiber MPs than granular MPs	requires precise control of electrolyte concentration and applied voltage (optimal: 0.05 M, 10 V); higher operational costs at non-optimal conditions	82–98.4% removal efficiency depending on MP type	municipal and industrial wastewater treatment systems	[66]
dissolved air flotation (DAF) with Al- and Fe-based coagulants	coagulation and flotation of MPs using air bubbles	C P	high PE MP removal efficiency: 96.10% (Al-based) and 70.56% (Fe-based); effective as a tertiary treatment in WWTPs; allows optimization through statistical modeling	lower efficiency with Fe-based coagulants compared to Al-based; requires precise control of pressure, pH, dosage, and flow rate	96.10% PE removal with Al-based coagulant; 70.56% with Fe-based coagulant	greywater treatment and advanced wastewater treatment in WWTPs	[67]
municipal sewage treatment plants (STPs)	multi-stage treatment including physical, chemical, and biological processes	P C B	high overall removal efficiency for MPs (>95%); capable of reducing MPs in reclaimed water to 0.59 ± 0.22 items/L; handles large volumes of wastewater	microfibers (average size: 1110.72 ± 862.95 µm) remain predominant in effluents; MPs make up 14.08% of total MPs released	>95% removal efficiency for a wide range of MP types including PET, PS, and PP	municipal wastewater treatment and water reclamation processes	[68]

[a]Type: B – biological; C – chemical; P – physical.

cal significance of cryophilic fungal species has been highlighted by studies showing their capacity to break down PET [46].

Biofilms can accelerate the breakdown process under cold conditions by generating enzymatically active microenvironments [71]. According to Dhiman et al., these microbial colonies stick to the surfaces of MPs and release enzymes that break down synthetic polymers into smaller, biodegradable particles [72]. Ojha et al. found that adding nutritional supplements sped up biofilm production in lab trials, suggesting that this strategy might be useful in nutrient-deficient lakes in the Himalayas [47]. The synergistic effects of hybrid biofilms that include psychrophilic bacterial and fungal species are being investigated in order to increase degrading efficiency [44].

There are several obstacles to bioremediation in alpine environments. It takes longer for plastic to degrade effectively at low temperatures because enzyme responses and microbial metabolisms are slowed down [73]. Himalayan lakes are also oligotrophic, which means they do not have a lot of nutrients. This can make it difficult for microbes to grow and for biofilm to form. To solve these problems, we might need new ideas like bioreactors designed for cold places or synthetic biology methods to improve the abilities of microbes already present [47].

5.3 Emerging sustainable approaches

5.3.1 Use of biofilms. Biofilms have attracted a lot of interest as a remediation method for MPs because of their ecological and biological flexibility. Biofilms are groups of microbes that form a protective covering made of extracellular polymeric substances (EPSs). These EPSs are made by the microbes themselves and stick to surfaces, such as MPs. The enzymes secreted by these microbial colonies have the ability to degrade synthetic polymers into smaller, biodegradable components. Tiwari et al. have recently demonstrated the effectiveness of biofilms formed by engineered microbial consortia in expediting enzymatic degradation in response to specific environmental conditions, such as low temperatures [42].

Biofilms are very beneficial in habitats such as Himalayan lakes. Biofilm-based remediation techniques are environmentally friendly, in contrast to chemical or physical remediation techniques that could disrupt local biodiversity. For example, even in oligotrophic environments, psychrophilic bacteria in biofilms may flourish at freezing temperatures and aid in the degradation of MPs. Studies have demonstrated that electrostatically modified biofilms enhance adherence to moving water systems, rendering them a viable option for large-scale applications [43]. Biofilms along with other methods, like adding nutrients or immobilized bioreactors, have been used in field trials to show that MPs can be permanently removed without causing secondary pollution [72].

5.3.2 Nanotechnology for degradation. Nanotechnology offers a novel method for the accurate and effective breakdown of MPs. Under UV light, nanomaterials such as ZnO and TiO_2 work as photocatalysts to break down MPs into CO_2 and water, which are safe for the environment. Photocatalysis produces reactive oxygen species (ROS), which attack polymer chains and cause oxidative cleavage. Studies have shown that, under ideal circumstances, this process is quite successful in degrading polymers such as PS [74].

Bionanomaterials, which are composite systems that combine nanotechnology with biological components (e.g., enzymes), are emerging as environmentally benign solutions in addition to independent nanoparticles. Enzyme–nanoparticle conjugates can target certain plastic polymers, enabling more rapid and targeted breakdown. Iron oxide nanoparticles have been shown to break down PS in both UV and natural light, which suggests they could be used in a range of environmental conditions [44]. Another prospective application is the integration of nanomaterials into filtration membranes, which results in the development of hybrid systems that are capable of simultaneously capturing and degrading MPs. These integrated methods are especially beneficial for isolated ecosystems, such as Himalayan lakes, where minimum ecological disturbance and resource efficiency are crucial [46].

Recent studies, for example, by Ojha et al. suggest that integrating degrading enzymes from biofilms with nanomaterial carries can enhance MP degradation under cold, UV-rich conditions [47]. Such synergies offer sustainable MP removal in remote high-altitude lakes. Future work should explore their performance under freeze–thaw cycles, low sunlight penetration, and high-altitude pH variability.

6 Nanomaterial applications in microplastic remediation

6.1 Role of photocatalysis in degradation

Photocatalysis uses nanomaterials to break down MPs by converting light energy, often UV or visible light, into ROS. These ROS, which include superoxide anions and hydroxyl radicals, attack the polymer chains of MPs. They either break the chains into smaller pieces or mineralize them into CO_2 and water. A lot of research is being done on the photocatalytic properties of nanomaterials like TiO_2, graphene oxide (GO), and ZnO. An excellent material for breaking down MPs in water systems is TiO_2, which is known for being stable, effective, and able to produce ROS when exposed to UV light [43].

The effectiveness of TiO_2 has been improved recently by doping it with nonmetals like sulfur and nitrogen or combining it with carbon-based compounds like graphene. According to Xiao et al., these changes make TiO_2 photocatalysts more effective in natural sunlight by letting more visible light pass through them [75]. ZnO has demonstrated potential as a result of its compatibility with UV light and high oxidative potential. Its nanostructured forms, such as nanorods and nanowires, provide more surface area, allowing for better interaction with MPs [76]. The incorporation of GO in composite materials not only improves photocatalytic activity, but it also serves a second purpose by adsorbing MPs prior to degradation.

The utilization of photocatalysts that have been engineered with defects is an emerging area. The defects in the crystal structure of nanomaterials trap light energy and enhance the production of ROS. According to Kim and Youn, these developments are essential to address the robustness and effectiveness of photocatalysts in a variety of environmental conditions [77].

6.2 Case studies of nanomaterial efficiency

The effectiveness of nanomaterials in the remediation of MPs has been confirmed in numerous experimental studies and real-world practical applications. Jeyaraj et al. found that after 12 h of UV irradiation, TiO_2 nanoparticles degraded PP MPs with an efficiency of more than 80% [76]. This demonstrates their capacity to quickly clean up waterways tainted by plastic. Researchers have also demonstrated that the combination of adsorption and photocatalysis enhances the degradation of PE and PET in GO-based composites. According to Uoginte et al., GO serves as a support matrix for these composites, stabilizing the photocatalyst and enhancing its interaction with MPs [78].

Another novel strategy is the use of multifunctional nanomaterials, such as ZnO–CuO composites, which have both antibacterial and strong photocatalytic activity. These substances provide long-term performance in natural water systems by not only breaking down MPs, but also preventing the development of biofilms [79]. The use of TiO_2 nanomaterials doped with Pt nanoparticles has also been investigated in case studies; these materials showed quicker breakdown rates for persistent PET MPs, highlighting the possibility of catalytically improved remediation techniques [80].

Nanomaterials such as ZnO have accomplished the removal of MPs from treated effluents in field tests conducted in wastewater treatment facilities. These tests were conducted under natural light and showed encouraging results. According to Goh et al., these results are especially important for expanding MP remediation technology to industrial applications [43]. Tables 4–6 presents a comprehensive comparison of various nanomaterials explored for MP remediation, detailing their synthesis methods, target pollutants, removal mechanisms, efficiency, and experimental conditions.

To improve clarity and compare functional mechanisms, the nanomaterials are grouped based on their primary MP removal strategy, that is, adsorption, photocatalysis, and magnetic/hybrid systems. Tables 4–6 highlight that adsorption and photocatalysis are the most prevalent mechanisms in nanomaterials to eliminate MPs, where metal oxides and carbon materials are particularly effective. Surface modification and environmental factors are crucial in controlling removal.

Table 4: Studies on adsorption-based nanomaterials for MP remediation.

Nanomaterial	Synthesis method	Target pollutants	Removal mechanism	Experimental conditions	Efficiency/ reusability	Ref.
sulfidised nano-zerovalent iron biochar	one-pot synthesis using sugarcane bagasse-derived biochar	amine modified NPs (AM100); sulfate modified NPs (SM100); malachite green (MG); alizarin yellow R (AY)	electrostatic attraction; dye degradation; Complexation; π–π interactions	pH: environmentally relevant conditions; instantaneous removal in <15 min	>85% 6 cycles	[81]
Fe and Al-modified chitosan (Fe-CHI and Al-CHI) ionotropic beads	modification of CHI with Fe and Al salts to form ionotropic beads	PET	adsorption via metal-ion interactions; pH-dependent protonation/deprotonation	optimal at low pH; reduced efficiency with increasing temperature	>70% 3 cycles	[82]
surface-modified nano Fe_3O_4 (–COOH, $–NH_2$, –OH)	functionalisation of Fe_3O_4 NPs with carboxyl, amine and hydroxyl groups	MPs: PE nutrients: NH_4^+–N and PO_4^3–P	electrostatic adsorption; hydrogen bonding; ion exchange	adsorption capacity: NH_4^+–N (18.45 mg/g), PO_4^{3-}–P (30.04 mg/g), PE (1611 mg/g)	62% (in freshwater), 70% (in seawater) –	[83]
aluminum chloride ($AlCl_3$) coagulant	coagulation and sedimentation process using $AlCl_3$ as a coagulant	carboxyl-modified PS NPs (PS–COOH, 50 nm)	electrostatic adsorption; intermolecular interactions; surface layer compression	optimal dose: 10 mg/L $AlCl_3$; pH: 3.5 to 8.5; temp.: 23 °C	96.6% (removal of 50 mg/L PS-COOH), 90.2% (removal in real surface water) –	[84]

Table 5: Studies on photocatalytic nanomaterials for MP remediation.

Nanomaterial	Synthesis method	Target pollutants	Removal mechanism	Experimental conditions	Efficiency/ reusability	Ref.
GO and nitrogen-doped TiO_2 (N-TiO_2) composites (GT13, GT11, GT31)	composite synthesis in varying weight ratios of GO:N-TiO_2	polyvinyl chloride (PVC)	photocatalysis; adsorption under dark and light conditions	work across all pH ranges (4, 7, 10); high thermal stability	>95% –	[85]
silver-doped TiO_2 (Ag/TiO_2) photocatalysts (AT1.5)	photo-assisted deposition method with 1.5% Ag loading	polyamide 66 (PA66)	photocatalytic degradation; enhanced light absorption and electron–hole pair separation	UVA irradiation for 4 h; optimal catalyst-to-PA66 ratio: 3:1	58.9% (in 4 h) 100% (at optimal ratio) –	[86]
high-pressure orthorhombic phase TiO_2	high-pressure torsion (HPT) method	PET	photoreforming; catalytic degradation and H_2 production	light exposure to generate formic acid, terephthalate, glycolic acid, and acetic acid	high efficiency –	[87]
ZnO NPs	photocatalyst under sunlight exposure	PP	photocatalytic degradation; formation of free radicals	sunlight as the light source; UV–vis DRS and EDS analysis showed polymer chain disintegration	high –	[79]
molybdenum trioxide (MoO_3) nanoflakes, nanobelts, and MoO_3/ single-walled carbon nanotube (SWCNT) nanocomposites	synthesis of MoO_3-based photocatalysts with SWCNT composites	PS NPs	photooxidative degradation under UV light; reduction in particle size and morphological transformation	UV irradiation for 24 h; PS NPs size reduced from 220 to 178 nm	>19% (with MoO_3 nanoflakes) –	[88]
indium oxide-rGO (In_2O_3-rGO) nanocomposite	metal oxide nanocomposite synthesis for photocatalysis	low density polyethylene (LDPE)	photocatalytic degradation under visible light; surface morphology transformation and chemical bond cleavage	visible light exposure for up to 50 h	99.47% –	[89]
BiOCl-ZrO_2 nanocomposite	solution casting method to blend BiOCl and ZrO_2 into LDPE film	LDPE	photocatalytic degradation under visible light; Type II heterojunction mechanism	visible light irradiation for 24 days at room temperature	48.67% –	[90]
porous hybrid nanocomposite (HNCP) with rGO	fabrication of porous hybrid nanocomposite with rGO to enhance surface area and adsorption capacity	PET	photocatalytic degradation under light; adsorption via high surface area and pore interaction	–	64% (photocatalytic) 31% (adsorption) –	[91]
Ru-incorporated g-C_3N_4 (Ru-gCN) nanocomposite	blending of Ru-gCN with LDPE	LDPE	photocatalytic degradation via heterojunction formation; Norrish Type I and II mechanisms	light irradiation for 24 h; optimal pH 3; temp.: 0, 50 and 70 °C	66.04% (0 °C) 74.51% (50 °C) 69.64% (70 °C) –	[92]

Table 5: Studies on photocatalytic nanomaterials for MP remediation. (continued)

TiO_2/ZnO hybrid nanoparticles with humic substances	solvothermal synthesis using agrifood biomass-derived humic substances	polylactic acid (PLA)	photocatalytic degradation under UVA and solar light; antimicrobial activity via ROS generation	–	15–23% (carbonyl index reduction) –	[93]
CuMgAlTi-R400 quaternary layered double hydroxide composite	fabrication of a multi-metal layered double hydroxide for photocatalytic applications	- PS - PE	photocatalytic degradation under visible light; reduction of particle size and formation of hydroxyl and carbonyl intermediates	visible light irradiation: 300 h	54.2% (PS) –	[94]
GO-ZnO nanocomposite	synthesis of GO-ZnO photocatalyst with an average ZnO crystallite size of 16.43 nm	LDPE	photocatalytic degradation under UV light; interaction of pH, temp., and catalyst dosage	- pH: 9.66 - temp.: 30 °C catalyst dosage: 1500 ppm; photodegradation: 2 h	39.47% (max. MP mass loss) –	[95]
Fe- and Ag-modified TiO_2 nanotubes	anodization of Ti plates in glycerol-based electrolyte Fe/Ag incorporation via successive ionic layer adsorption and reaction (SILAR)	PE	photocatalytic degradation under UVC light; bactericidal effect through ROS generation	90 min photoreactor test	18% (weight loss) –	[96]
Ag/TiO_2 catalyst (3% Ag)	photoassisted deposition (PAD) method with 1%, 3%, and 5% Ag doping	PE	photocatalytic degradation under UV light; enhanced microbial disinfection via ROS	2000 rpm stirring; UV irradiation for 4 h	81% –	[97]
Fe-doped ZnO (Fe-ZnO) NPs	green synthesis using Hibiscus rosa-sinensis leaf extract	LDPE	photocatalytic degradation under sunlight; generation of ROS for antimicrobial action	sunlight exposure	high –	[98]

Table 6: Studies on magnetic and hybrid nanomaterials for MP remediation.

Nanomaterial	Synthesis method	Target pollutants	Removal mechanism	Experimental conditions	Efficiency/ reusability	Ref.
TiO_2 and CuO-modified polyvinylidene fluoride (PVDF) nanofibrous composite membranes	needle-free electrospinning of PVDF nanofibers with lamination and modification using alkaline treatment, biosurfactant, TiO_2, and CuO particles	MPs (0.5 µm); oil in oil-water emulsions	physical separation; antifouling through TiO_2 and CuO particles	BS-modified membranes: >9000 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ permeability for MP separation; TiO_2-modified membranes: high oil rejection (≈95%)	99.99% (MP) 95.30% (oil) –	[99]

Table 6: Studies on magnetic and hybrid nanomaterials for MP remediation. (continued)

fly ash-loaded magnetic nanoparticles (FAMNPs)	synthesis of magnetic nano-adsorbent using fly ash	PS	adsorptive uptake via magnetic separation	pH 8.5; FAMNPs dose: 0.03 g; adsorption capacity: 29.12 mg/g	high adsorption capacity –	[100]
magnetic composite NPs (FNP)	synthesis of Fe_3O_4 magnetic cores with eco-friendly coatings (silicon dioxide, CHI, gelatine)	PET (5–30 µm)	magnetic sedimentation; heteroaggregation of FNP and PET	magnetic field strength: 0.44 T; optimal dose: 0.002 g/L; sedimentation time: 0.5 h	>98% –	[101]
magnetic ZIF-8 NPs (Nano-Fe@ZIF-8)	synthesis of magnetic MOFs with Fe and Zn (II) components	PET	magnetic aggregation and retrieval; catalytic depolymerisation	depolymerisation with ethylene glycol at 180 °C; rapid process: 30 min	high –	[102]
nickel/reduced graphene oxide (Ni/rGO) nanocomposite	magnetisation of rGO using Ni NPs	PS	adsorption via hydrophobic interactions; magnetic separation	maximum adsorption capacity: 1250 mg/g; follows Langmuir isotherm and pseudo second-order kinetics	high 3 cycles	[103]
hydrogen titanate nanotubes (HTNT@ZIF-67) nanocomposite	combination of HTNT with zeolite imidazolate frameworks (ZIF-67) at ambient temperature	MPs from personal care products (PCPs) and cosmetic products	adsorption; catalytic oxidation with H_2O_2	–	99% (adsorption) 97% (catalytic oxidation) 6 cycles	[104]
Fe_3O_4@PDA (polymerised dopamine-coated Fe_3O_4 NPs)	coating of mesoporous Fe_3O_4 NPs with adhesive PDA to mimic coral reef structures	MPs	adsorption through hydrogen bonding, π–π stacking, and hydrophobic interactions	–	98.5% –	[105]
laundry filter system with Fe_3O_4 and $CaCO_3$	incorporation of magnetic (Fe_3O_4) and carbonate ($CaCO_3$) particles into filter design	MP	simultaneous removal of hydrophobic and hydrophilic MPs; adsorption and filtration	–	78.3–89% –	[106]
n-butylamine modulated magnetic ZIF-8 (nano-Fe@ZIF-8)	synthesis of magnetic ZIF with *n*-butylamine in water at room temp	PS (1.1 µm)	adsorption and magnetic separation; fast removal of MPs and phenolic compounds	dosage: 20 mg	≥98% –	[107]
superhydrophobic magnetic adsorbents (Fe_3O_4@Cn)	liquid phase deposition of Fe_3O_4 with saturated fatty acids (C12, C14, C16, C18)	PS	adsorption through electrostatic and chemical bonding interactions; magnetic separation	–	92.89% (Fe_3O_4@C12) 809.29 mg/g (adsorption capacity) –	[108]
magnetic effervescent tablet with deep eutectic solvent (DES)	formulation of effervescent tablet containing DES, Fe_3O_4 magnetic NPs, sodium carbonate, and tartaric acid	PS	combined extraction and adsorption through DES and magnetic NPs; effervescence aids in rapid dispersion and sorption	optimal conditions: 94.0 ± 0.8% extraction efficiency; detection via fluorescence-assisted method	94% –	[109]
multiwalled carbon nanotube (MWCNT) membrane	fabrication of lightweight, freestanding, and flexible MWCNT membranes	MPs	physical sieving through narrow pore size (≈16 nm); hydrophobic surface for self-cleaning	contact angle: ≈148°; high porosity: 56%; pressure drop: ≈139.7 Pa	>99% –	[110]

Table 6: Studies on magnetic and hybrid nanomaterials for MP remediation. (continued)

magnetic carbon nanotubes (M-CNTs)	synthesis of M-CNTs for adsorption and magnetic separation	PE; PET; PA	adsorption of MPs onto M-CNTs; magnetic separation for removal	M-CNTs: 5 g/L; time: 300 min; max. adsorption capacity: 1650 mg/g (PE), 1400 mg/g (PET), 1100 mg/g (PA)	100% (MP removal from solution) ≈80% (MP removal after 4 reuse cycles) 4 cycles	[111]

6.3 Tailoring nanomaterials for low-temperature, high-UV environments

The Himalayan lakes and other high-altitude environments provide specific challenges for MP removal because of their low temperatures, intense UV radiation, and scarcity of organic materials. It is imperative that nanomaterials are engineered to maintain photocatalytic efficiency under cold conditions while simultaneously utilizing the abundant UV radiation [75]. It has been demonstrated that the light absorption of ZnO and TiO_2 is improved by defect engineering, such as the introduction of oxygen vacancies. According to Kim and Youn, these defects trap light energy, which lowers charge carrier recombination rates and increases ROS generation, even below freezing temperatures. It has also been suggested that hybrid nanomaterials, which include photocatalysts and thermal insulators, can minimize the impacts of temperature during remediation while maintaining optimum activity [77].

GO–metal oxide composites are another promising approach. GO may be combined with TiO_2 or ZnO to create materials that have both adsorption and photocatalytic properties, which improves their ability to absorb and break down MPs. They are perfect for harsh and isolated environments because of their resilience and flexibility [79]. The development of scalable technologies for producing nanomaterials is essential for their practical application. Green chemistry methods, such as plant-based precursors or bioinspired templates, have been successfully used to synthesize nanomaterials with high photocatalytic efficiency and minimal environmental effect [77].

Despite their high efficiency, nanotechnology-based remediation solutions may face deployment challenges in remote Himalayan regions due to high initial cost, maintenance needs, and lack of infrastructure. Scalable, low-cost nanocomposites or hybrid bionanotechnology systems adapted for cold climates represent a promising direction for future trials.

7 Ecotoxicological impact and risk assessment

MP pollution of high-altitude ecosystems is a new issue with significant ecological and health effects. Because of low temperature, high levels of UV irradiation, and slow biodegradation rates, MPs remain long enough in aquatic environments, boosting their ecotoxicological impact [4]. This section covers the consequences of MPs for aquatic biodiversity, bioaccumulation within the food chain, additive toxicity of plastic, and likely long-term health effect on humans and ecosystems.

7.1 Bioaccumulation of microplastics in the Himalayan food web

MPs are consumed by numerous aquatic animals, such as plankton, benthic invertebrates, and fish, resulting in bioaccumulation and biomagnification in the Himalayan food web [112]. MP ingestion has been documented in freshwater fish populations of high-altitude lakes, where particles accumulate in the gut and gill tissues and interfere with normal physiological functions [113]. The low molecular weight of MPs, and particularly nanoparticles (NPs), allows them to easily translocate into organs and tissues resulting in inflammation, oxidative stress, and metabolic disturbance in aquatic life [114].

MPs also act as carriers of hydrophobic organic pollutants such as pesticides, heavy metals, and persistent organic pollutants, which are more harmful when ingested [23]. Trophic transfer issues are generated by the bioaccumulation of MPs in fish, with birds and mammals being exposed to tainted prey, which might have implications at the ecosystem level. The occurrence of MPs in freshwater fauna of the Himalayas also implies that native human populations dependent upon fish as food could be endangered by MP ingestion.

7.2 Toxicity from plastic additives and degradation byproducts

MPs come from various sources and are responsible for environmental and human health risks. First, plastics are manufactured with chemical additives such as phthalates, bisphenol A (BPA), and brominated flame retardants, which are endocrine disruptors and carcinogens [115,116]. Second, MPs have a large surface-area-to-volume ratio that enables them to adsorb persistent organic pollutants, polycyclic aromatic hydrocarbons, and heavy metals, such as Cd, Pb, and Hg from bodies of water [5,117]. Third, photodegradation and oxidative weathering of

MPs upon UV light and temperature fluctuations release toxic byproducts and nanoplastics, which are more bioavailable and more easily taken up by cells [118,119].

These collective mechanisms of toxicity are a threat to freshwater biodiversity and human health. Their activity is particularly vital to individuals relying on such water for drinking, agriculture, and fisheries. Their occurrence and persistence are therefore of utmost significance to Sustainable Development Goal 3 (SDG 3, Good Health and Well-Being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water). Apart from their physical structure, MPs are also significantly hazardous through the additives and byproducts that they release into the environment [120,121].

7.3 Long-term implications for ecosystem and human health

Long-term exposure to MPs can potentially alter fundamental ecological processes such as nutrient cycling and primary production through the influence on keystone organisms in the ecosystem [11]. Microbial community disruption due to MP pollution has been observed, which can disrupt the balance of prevalent nutrient conversions in freshwater ecosystems [113]. From a public health perspective, populations residing around Himalayan lakes and dependent on these freshwater basins for agriculture, drinking water, and fishery resources are more likely to be exposed to MPs. Although comprehensive data on MP bioaccumulation in Himalayan populations are currently lacking, the detection of MPs in Himalayan spring water and fish highlights potential exposure. This gap underscores the urgent need for region-specific health monitoring and food safety assessments. Recent studies report the identification of MPs in bottled and mountain spring-collected tap water samples and their bioaccumulation in the human body upon ingestion as an emerging issue [10].

With increasing evidence of MP pollution in remote, high-altitude ecosystems, there is a pressing need to limit their impacts. Establishment of robust surveillance regimes, policy measures, and ecofriendly waste disposal methods in the Himalayas is required. Future research needs to include the transport and fate of MPs in extreme ecosystems, their synergistic impacts with other pollutants, and their long-term effects on biodiversity and human health.

8 Policy frameworks and management strategies for MP pollution

8.1 Current policies addressing MP pollution

MP pollution has emerged into the limelight internationally and has led to many policies and regulations addressing its effects. At the international scale, the United Nations Environment Programme (UNEP) has demonstrated significant initiative in the form of deliberations of a Global Plastic Treaty with an aim to constitute legally binding plastic reduction instruments along with MP reduction. Consequently, the European Union (EU) also deliberately limited incorporated MPs in the EU Microplastic Restriction Proposal of the REACH regulation of cosmetics, cleaning products, and agricultural products in a bid not to release MPs into the environment [122].

National governments have also implemented policies to avoid MP pollution. The United States enacted the Microbead-Free Waters Act (2015), which banned microbeads from plastic in personal care products. California and other states have more recently enacted even more stringent regulations for the tracking of MPs in drinking water. In India, the Plastic Waste Management Rules (amended 2016 and 2021) prohibit microbeads in cosmetics and impose extended producer responsibility (EPR) on producers of plastic to enable recycling and green disposal. China, in turn, has initiated its plastic pollution control action plan, and it put special emphasis on reducing MPs through strict prohibitions on some plastic imports and improved waste management practices [123]. The key national and regional policy frameworks aimed at mitigating MP pollution are discussed in Supporting Information File 1, Table S1.

However, these advancements are not well followed up with the implementation of the policies, especially in the global south. Standardized tests and monitoring procedures for air-, water-, and food-borne MPs do not exist in the majority of countries. Furthermore, opposition from industries to phasing out synthetic MPs and lack of sufficient public awareness slow down the process. Upcoming policies must address more monitoring, industry compliance, and investment in sustainable alternatives to plastics [124].

8.2 Community-driven approaches in the Himalayan context

The Himalayas experience MP pollution from tourism, rampant waste dumping, and plastic waste transport as a result of glacial melts [125]. Locally driven interventions have been helpful steps in the fight against such issues to ensure and hold back plastic pollution. These successful citizen-led initiatives among others are single-use plastic prohibitions at the local government level and waste management programs. Sikkim took the lead as the first Indian state to prohibit single-use plastics back in 1998, and later Ladakh, Himachal Pradesh, and Bhutan followed suit [126]. The prohibitions have been implemented through joint efforts of citizen volunteers, NGOs, and local administrations.

Citizen science programs in recent times have played a vital role in monitoring and alleviating MP pollution in Himalayan rivers. WWF, Eco Himal, and The Himalayan Cleanup are organizations that have mobilized local communities and school children to collect and analyze water samples regarding MP contamination [127]. In Nepal, zero-waste trekking initiatives at Everest Base Camp and Annapurna Circuit encourage hikers to collect waste, reducing the plastic waste in these wilderness areas [128,129].

Apart from this, novel plastic exchange initiatives have been initiated in far-flung Himalayan villages. By these programs, citizens can trade plastic waste collected by them for essential items such as rice, vegetables, or school supplies, encouraging waste management practice among citizens. By promoting awareness campaigns for plastic-free religious pilgrimages such as the Hemis Festival in Ladakh, environmentally friendly practices among pilgrims and tourists have been encouraged [130]. With these initiatives, however, come challenges in collection infrastructure, enforcement of policy, and funding local efforts. For these community-driven strategies to scale up, however, more government support, inter-border cooperation, and coordination with formal waste management systems are necessary.

8.3 Suggestion for monitoring and regulations

The increasing presence of MPs in the environment calls for effective monitoring systems and stringent regulatory systems to mitigate their impacts. Governments and international agencies must give the highest priority to standardized detection methods, legislative measures, industry accountability, and public awareness to combat this issue effectively.

First, detection and monitoring systems have to be boosted in order to build a baseline of MP pollution control. Standard protocols created by international organizations can monitor MPs in a variety of environmental matrices. Analysis methods such as Raman spectroscopy, FTIR, and pyrolysis-GC/MS have been accepted as highly effective to trace the origins of MPs and compositions [131]. Public engagement in monitoring programs, such as citizen science initiatives, plays a crucial role in data collection and raising awareness [132].

Regulatory systems play a key part in managing MPs pollution. Bans of microbeads added intentionally have been put into practice by some countries, such as Canada and the UK, where microbeads are banned in cosmetics [133]. The EU has placed restrictions under REACH regulation to restrict commercial use of MPs [134]. France has taken further steps by mandating that new washing machines be equipped with microfiber filters by 2025 to reduce microfiber emissions [132]. In addition, the United States has taken actions such as the “Save Our Seas 2.0 Act”, which provides grants to enhance wastewater treatment infrastructure and reduce MPs contamination [135].

Since wastewater treatment plants (WWTPs) are significant contributors to MP pollution, upgrading filtration technology is crucial. Germany and Switzerland have also enhanced their WWTPs to add more advanced membrane bioreactors and electrocoagulation systems to minimize MP discharge [136]. Implementation of microfiber filters for laundry, already taken up in France and debated in Australia, additionally limits MP discharge from clothes [137]. Encouraging a circular economy model can minimize plastic waste generation at the industrial level. EPR policies have been proposed to hold manufacturers accountable for post-consumer plastic waste, as emphasized in the EU’s Circular Economy Action Plan [138]. Additionally, industries should be incentivized to develop biodegradable alternatives, such as bioplastics, to reduce dependency on conventional plastics [139].

Due to the transboundary character of MP pollution, international collaboration is necessary. The 2022 UN Global Treaty on Plastics, which was signed by 175 countries, is a major milestone toward legally binding global agreements on plastic waste management [140], including MP cross-border policy coordination and research, supported by efforts such as the global partnership on marine litter (GPML), strengthening global action against MP pollution [133]. A comprehensive solution to MP pollution must involve interdisciplinary measures that combine scientific monitoring, strict legislation, technological innovation, and cooperation from industries. Strengthened policies, enhanced purification techniques, and international cooperation will help governments to reduce MP contamination by a considerable extent, creating a safer environment for future generations.

9 Research gaps and future directions

Even with increasing recognition of MP pollution, there are still major research gaps regarding fate, impact, and mitigation of MPs. One such challenge is the absence of a standardized monitoring system, which causes variability in data collection between studies. More advanced spectroscopic and AI-based detection systems need to be investigated for enhanced accuracy and efficiency. Furthermore, the long-term destiny, transport, and bioaccumulation of MPs in the different compartments of the environment have not been well established, especially about how they interact with other contaminants and can potentially be transferred along food webs. Human health effects of MPs are another important knowledge gap since toxicity mechanisms, exposure routes, and long-term risks are still not well established. It should be directed towards understanding ingestion, inhalation, and dermal exposure pathways, as well as to MP ability to act as a vector of toxic chemicals and microorganisms.

Emerging MP removal technologies and regulatory policies also need to be developed. Existing wastewater treatment facilities are not effective in completely filtering MPs, so membrane filtration, electrocoagulation, and biodegradable plastic substitutes need to be improved. While some countries have implemented bans on microbeads, comprehensive regulations addressing other sources, such as textiles and industrial waste, are still lacking. A stronger policy framework, encompassing extended producer responsibility and circular economy models, is required to constrain MP pollution. Socioeconomic impacts, including impacts on fisheries and tourism, must be better understood to improve policymaking. Future studies must take a multidisciplinary approach with the inclusion of environmental science, public health, engineering, and policy to develop holistic strategies to mitigate MP pollution and ensure long-term sustainability.

Conclusion

This review points out that among the serious environmental problems created by tourism, atmospheric deposition, and melting of glaciers is microplastic contamination of Himalayan Lakes. The severity of climatic conditions and the need for precise analytical methods make the assessment of microplastic contamination in such remote environments difficult.

Physical technologies such as adsorption and filtration with materials such as nanomaterials and biochar can be used to remove microplastics from water. But they may need high energy input. Chemical processes such as oxidation and coagulation can degrade microplastics, but they may produce secondary pollutants. Biological processes, especially microplastic degradation aided by biofilms and microbial consortia, are challenging regarding long-term sustainability and effectiveness in cold, high-altitude environments. Nanotechnology-based treatments, especially photocatalytic degradation, are strongly effective in removing microplastics with less environmental damage. The most promising approach, balancing effectiveness with sustainability, is a blend of biological and nanotechnology-based remediation, keeping in view the eco-sensitive nature of the Himalayan lakes. For effective microplastic reduction in natural aquatic environments, future studies must be directed towards field-scale application and long-term ecological consequences of these technologies.

This review fills an essential knowledge gap by specifically examining MP pollution in high-altitude Himalayan lake ecosystems. Through the incorporation of knowledge on glacial melting, tourism pressure, and groundwater connectivity, the review adds to a regional-scale understanding of MP dynamics. In addition, the research discusses specific recommendations for monitoring and mitigation, including the application of nanotechnology-based solutions and SDG-linked governance frameworks. These individual contributions, in total, close the research gap that was identified and provide a roadmap for future research and policy intervention into cold-climate freshwater systems.

Supporting Information

Supporting Information File 1

Additional table.
[https://www.beilstein-journals.org/bjnano/content/supplementary/2190-4286-16-148-S1.pdf]

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Author Contributions

Sameeksha Rawat: conceptualization; data curation; investigation; methodology; visualization; writing – original draft. S. M. Tauseef: resources; supervision; validation; writing – review & editing. Madhuben Sharma: project administration; supervision; validation; writing – review & editing.

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Data Availability Statement

Data sharing is not applicable as no new data was generated or analyzed in this study.

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