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Review

Innovative Approaches to Mitigating Microplastic Pollution in Effluents and Soils

Solange Magalhães [1,2], Luís Alves [1], Bruno Medronho [2,3], Ida Svanedal [2], Magnus Norgren [2] and Maria Graça Rasteiro [1,*]

[1] CERES, Department of Chemical Engineering, University of Coimbra, Pólo II, R. Sílvio Lima, 3030-790 Coimbra, Portugal; solange.magalhaes@miun.se (S.M.); luisalves@ci.uc.pt (L.A.)
[2] Surface and Colloid Engineering, FSCN Research Centre, Mid Sweden University, SE-851 70 Sundsvall, Sweden; bfmedronho@ualg.pt (B.M.); ida.svanedal@miun.se (I.S.); magnus.norgren@miun.se (M.N.)
[3] MED—Mediterranean Institute for Agriculture, Environment and Development, CHANGE—Global Change and Sustainability Institute, Faculdade de Ciências e Tecnologia, Universidade do Algarve, Campus de Gambelas, Ed. 8, 8005-139 Faro, Portugal
* Correspondence: mgr@eq.uc.pt

Abstract

Microplastic pollution represents a significant environmental challenge, as microplastics accumulate in effluents and soils, causing serious risks to ecosystems and human health. Efficient removal of these contaminants is essential to mitigate their potential adverse effects. This review summarizes and critically analyses current methods for the removal of microplastics from effluents and soils, focusing on their effectiveness, advantages, and limitations. Conventional techniques—including filtration, flotation, chemical coagulation, flocculation, and adsorption—are discussed in the context of wastewater treatment and soil remediation. Emerging approaches, such as flocculation processes with special focus on the application of bio-based flocculants, are also highlighted as promising solutions. Key challenges in microplastic removal, including the diversity of microplastic types, their small size, and the complexity of environmental matrices, are addressed. This work intends to contribute to the urgent need for further research to develop more efficient and sustainable strategies for microplastic removal from environmental systems.

Keywords: microplastic; microplastic removal; effluents; soil; remediation; wastewater treatment; flocculation; adsorption; bioremediation

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1. Introduction

By 2050, plastic waste in the environment is projected to reach 121 million metric tons [1], with the total volume of plastics expected to approach 33 billion tonnes. In this regard, microplastics (MPs) have emerged as one of the most concerning environmental challenges of the 21st century [2]. The definition and classification of MPs has evolved over time, and today MPs are recognized as plastics found in the environment across a wide range of sizes [3]. Plastic particles are commonly categorized into five classes based on their size: nanoplastics (NPs) (<1 μm), MPs (from ≥1 μm to <5 mm), mesoplastics (from ≥5 mm to 5 cm), macroplastics (from >5 to 50 cm), and megaplastics (>50 cm) [4]. Small plastic particles originate from various sources, including the degradation of larger plastic debris, the leaching and discharge of synthetic fibers from textiles, and the release of MPs during industrial processes [5]. Their presence in effluents, including wastewater from urban and industrial origins, agricultural sources, and soils, has raised significant concerns about their long-term environmental and health impacts (see Figure 1) [6,7].

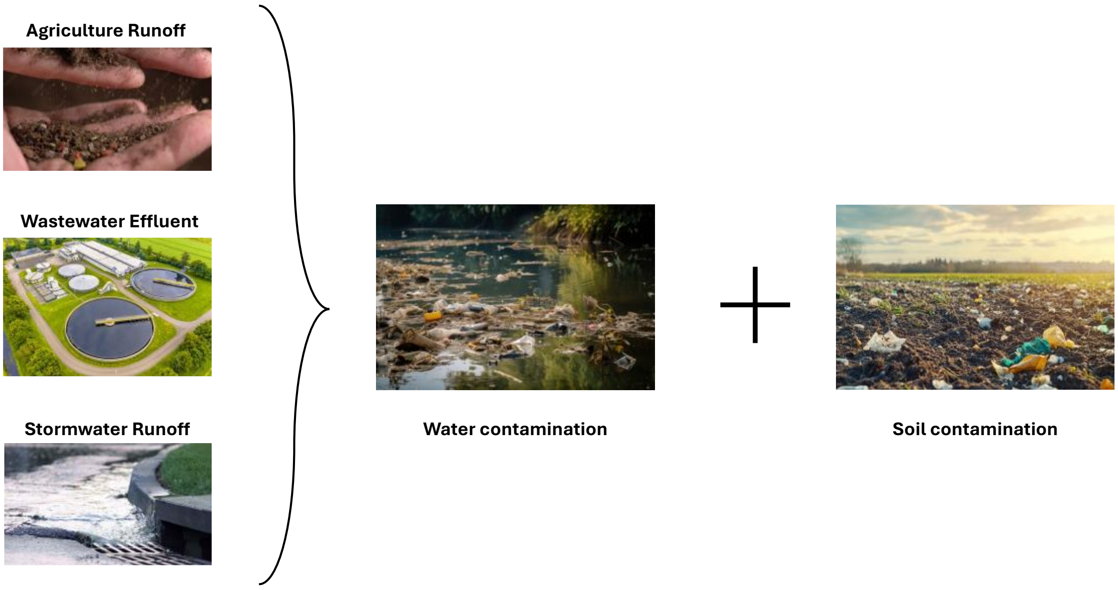

Figure 1. Pathway for MPs entering aquatic ecosystems, illustrating main sources such as urban and industrial wastewater effluents. (adapted from Wang et al. [8]).

Recent studies have highlighted the ubiquity of MPs, which are now detected not only in aquatic and terrestrial environments, but also in the atmosphere and within living organisms [9–11]. This widespread distribution renders both risk assessment and remediation efforts more difficult. Analytical challenges persist, as the detection and quantification of MPs, especially at the nano-scale, are limited by current methodologies, and there is still no universally standardized protocol for their separation and analysis [12]. Furthermore, the diversity in size, shape, polymer type, additives, and surface chemistry of MPs often implies the integration of multiple removal strategies, combining physical, chemical, and biological approaches [3,13].

As emerging contaminants, MPs in effluents and soils represent substantial threats to ecosystems, wildlife, and potentially human health. In aquatic systems, MPs can be ingested by marine organisms, leading to physical harm, chemical contamination, and bioaccumulation along the food chain [14]. Similarly, in soils, MPs may affect soil structure, microbial activity, and plant growth, thereby disrupting terrestrial ecosystems [15,16]. With the global accumulation of MPs continuing to rise, the need for effective removal strategies is increasingly urgent. Over the past few decades, a variety of methods have been developed and tested to address this growing issue. These range from conventional techniques, such as filtration and chemical coagulation–flocculation, to more advanced approaches involving bioremediation, electrochemical treatments, and the use of nanomaterials [17]. Emerging technologies, including advanced adsorbent materials and catalytic conversion processes, offer promising advantages for more effective and sustainable remediation [18]. However, each method has its own limitations—applicability being one of them—as each method is dependent on the specific environmental matrix and the types of MPs involved. This review aims to provide a comprehensive overview of the current methods for removing MPs from aqueous effluents and soils. By evaluating the effectiveness of different techniques and their associated challenges, we seek to highlight the most promising solutions for reducing MP pollution. Additionally, emerging technologies and strategies are explored to address the increasing complexity of contamination by MPs. The ultimate goal is to identify sustainable and efficient approaches for the removal of MPs from environmental systems, with a focus on enhancing treatment processes and mitigating MPs' widespread ecological impacts. While several previous reviews have addressed MP contamination and removal in specific environmental compartments, this work stands out by providing an integrated assessment of both aqueous effluents and soils, two major and interconnected reservoirs for MP pollution. Importantly, this review not only synthesizes the current state-of-the-art in conventional and emerging removal techniques, but also critically compares their efficacy, sustainability, and practical implementation barriers across different environmental matrices. Moreover, particular emphasis is placed on recent advances in analytical methods for MP detection and on the prospects of hybrid and multifunctional technologies—areas often underrepresented in earlier reviews—as well as limitations of regulatory and policy challenges and lacks. By systematically highlighting research gaps, the limitations of current approaches, and the potential of novel materials and combined strategies, this work offers a forward-looking perspective and actionable insights for both researchers and practitioners. Thus, the review sets itself apart by its comprehensive scope, critical comparative analysis, and emphasis on cross-disciplinary next-generation solutions for MP remediation.

2. Microplastic Occurrence and Impacts

MPs are widely distributed across diverse environments due to factors like industrial activity, urban runoff, and atmospheric transport, which can carry them even to remote areas. Beyond physical contamination, they serve as carriers for harmful pollutants and microorganisms, posing additional ecological risks. Understanding the sources, distribution, and impacts of MPs in effluents and soils is crucial for developing effective removal strategies. However, monitoring and quantifying MPs in these environments remains challenging due to the limitations of current analytical methods, involving sample preparation, detection limits, and the lack of standardized protocols. These challenges hinder the comparability of results across studies and make the development of regulatory guidelines more difficult.

2.1. Microplastics in Aqueous Effluents

Effluents, particularly from domestic and industrial wastewater treatment plants (WWTPs), industrial discharges, and agricultural runoff, are the major pathways through which MPs enter aquatic ecosystems [19]. Domestic and industrial effluents often contain MPs originating from the degradation of larger plastic items and the release of synthetic fibers from textiles [20,21]. Studies have reported that a single garment can release between 1900 and 1,000,000 fibers per wash [22]. For similar washing loads (5–6 kg), polyester fabrics can release over 6,000,000 fibers, while acrylic fabrics release around 700,000 fibers [23,24]. Due to their small size and buoyancy, these particles are easily transported through wastewater systems and often escape conventional filtration processes, ultimately reaching the receiving water bodies. Despite their primary role in removing organic and inorganic contaminants, wastewater treatment facilities are often ineffective at removing MPs. These particles can persist in the environment for hundreds or even thousands of years, undergoing further fragmentation through mechanical and photochemical processes [25]. Atmospheric deposition is another important pathway for MP contamination. For instance, Liao et al. (2021) found a higher abundance of airborne MPs at an urban transit station (287 ± 72 MPs/m^3) compared to rural farmland (137 ± 57 MPs/m^3), wetland (97 ± 33 MPs/m^3), and mountain (70 ± 18 MPs/m^3) sites [26]. Similarly, Dris et al. (2016) reported that urban areas in the Greater Paris region exhibited higher atmospheric fallout of MPs (110 particles/m^2/day) than suburban areas (53 particles/m^2/day) [20]. In Portugal, a country with a significant textile industry, MPs constitute a substantial fraction of contaminants in industrial areas and estuaries [27]. A recent study in the coastal regions of Arrábida and Setúbal, Portugal, revealed MP concentrations averaging 52.9 ± 31.9 particles$\cdot$kg^{-1} of sediment, with higher levels near the Sado estuary (1042.8 ± 430.8 particles$\cdot$kg^{-1} of sediment) [28]. Further north, Godoy et al. (2023) observed median MP concentrations of 236 ± 156 particles$\cdot$kg^{-1} (dry weight) in sediment samples and 68 ± 46 particles per square meter on Costa Nova beach [29]. Microspheres were the predominant morphology in the studied Portuguese effluents, constituting over 90% of total MPs, with an average size below 200 µm. Almeida et al. (2024) also reported a significant MP presence in the Lima River estuary, mainly particles smaller than 3 mm, predominantly in fiber form [30]. As mentioned, this abundance, especially of fibers, is likely linked to the strong textile industry in northern Portugal. The distribution of MPs along the Portuguese coast is influenced by many oceanographic phenomena, including seasonal upwelling, river plumes, and currents such as the Iberian Pole Current [31].

2.2. Microplastics in Soils

MPs are also prevalent in soils, primarily due to the application of contaminated effluents for agricultural irrigation and the use of biosolids as fertilizers (e.g., sewage sludge), which can introduce large quantities of MPs into the soil matrix [32,33]. Also, agricultural practices, such as the use of greenhouses, can result in large amounts of MPs being deposited in soils. These practices result in the direct deposition of MPs into terrestrial ecosystems. The presence of MPs in soils raises significant concerns for soil health and ecosystem functionalities [16]. MPs can alter soil structure, porosity, and water retention capacity, potentially disrupting plant growth and soil microbial communities. Several mechanisms may explain the variable impacts of MPs on soil [34]. Firstly, some MPs contain additives such as phosphorus-based antioxidants, nitrogen, and chlorine, which can be released into the soil after mineralization [35]. Secondly, MPs have a high adsorption capacity and may adsorb nutrients, altering their availability [36]. Over time, weathering and oxidation increase the porosity and surface charge of MPs, enhancing their adsorption capacity [37]. For example, MPs can adsorb bivalent metals like Cu^{2+} via electrostatic interactions, and their surface charge can influence the adsorption of various nutrients [38]. Third, soil nutrient cycles are regulated by microbial processes, and MPs can affect these cycles by altering microbial community composition and activity [39]. Changes in soil phosphorus availability, for instance, are linked to microbial-mediated inorganic phosphorus dissolution and organic phosphorus mineralization. In addition, ingestion of MPs by soil-based organisms, such as earthworms, has been shown to cause physical harm, alter reproduction rates, and interfere with nutrient cycling [40]. Furthermore, MPs can also accumulate in the food chain, potentially reaching higher trophic levels and posing risks to human health through the consumption of contaminated crops or animals [41,42], in general. The persistence of MPs in soils is particularly concerning, as these particles are resistant to biodegradation and can remain in the environment for extended periods. The use of sewage sludge as a nutrient source and of wastewater in irrigation introduce even more MPs into soils annually than into oceans [43]. It is estimated that between 125 and 850 tons of MPs per million inhabitants are added to European agricultural soils each year [44]. Sewage sludge can contain between 4196 and 15,385 MP particles per kilogram. In developed countries in Europe and North America, about 50–60% of sewage sludge is used as fertilizer, and similar practices are observed in developing countries such as Pakistan [45,46]. In Portugal, for example, the agricultural application of sludge is regulated under national legislation that aligns with EU directives, requiring strict monitoring and compliance to safeguard environmental and public health. This regulation includes the analysis of contaminants, limits for heavy metals, pathogenic agents, and other substances. However, there are currently no established standards for the identification and quantification of MPs in sludge [47]. In China, approximately 0.156 million tons of MPs (corresponding to 1.56×10^{14} particles) are introduced into the environment annually via sludge use [48,49].

2.3. Environmental and Health Implications

Both effluents and soils act as critical pathways for MP pollution, contributing to widespread environmental contamination. In aquatic environments, MPs can be ingested by a wide range of organisms, from plankton to larger marine species, leading to physical damage, chemical contamination, and the potential bioaccumulation of harmful substances; see Figure 2 [50–52]. MPs also act as carriers for toxic pollutants, such as pesticides and heavy metals, further worsening their potential environmental and health impacts [53,54]. In soils, MPs disrupt ecological processes by altering the soil structure and affecting the activity of microorganisms essential for nutrient cycling and organic matter decomposition. Over time, the accumulation of MPs may lead to reduced soil fertility and an overall decline in soil health, with potential consequences for agriculture and food security; see Figure 3 [55].

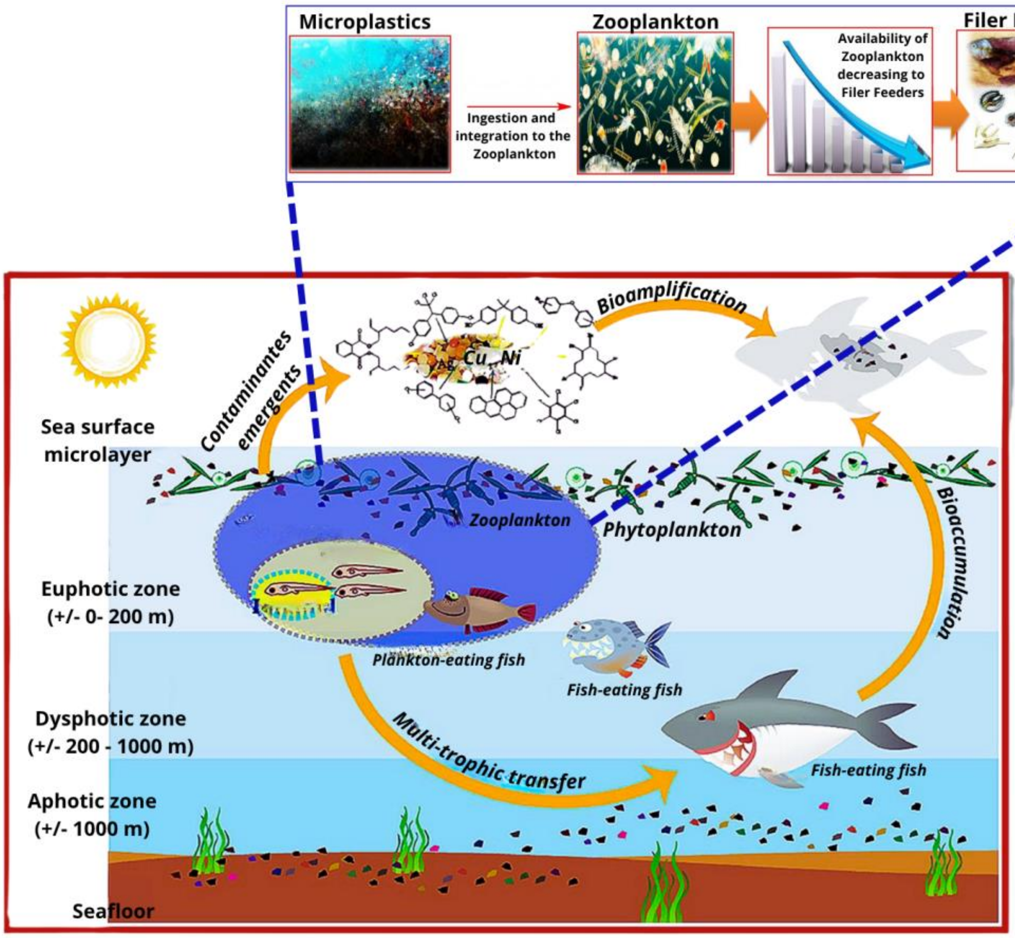

Figure 2. Schematic overview of the impacts of MPs on aquatic ecosystems. Adapted from Ali et al. (2024) [50] with permission from Elsevier.

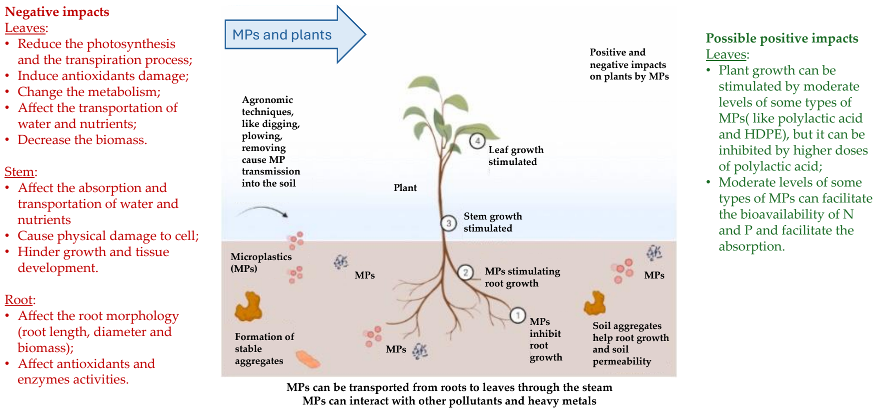

Figure 3. Illustration of the effects of MPs on soil and plants. The figure emphasizes the ecological risks associated with MP contamination in terrestrial environments. Adapted from Rafa et al. (2024) [54] with permission from Elsevier.

3. Analytical and Regulatory Challenges

Monitoring and quantifying MPs in effluents and soils present significant analytical challenges [56,57]. Current methodologies, summarized in Figure 4, such as density separation and spectroscopic analysis (e.g., FTIR, Raman), often face limitations regarding detection limits, sample throughput, and the ability to distinguish between plastic types or sizes, especially for NPs [58–60]. The absence of standardized protocols complicates data comparison across studies and hinders the development of regulatory guidelines. Additionally, the lack of specific regulatory frameworks for MPs in the environments of many countries further confuses mitigation efforts, highlighting the need for international collaboration and harmonized standards [61].

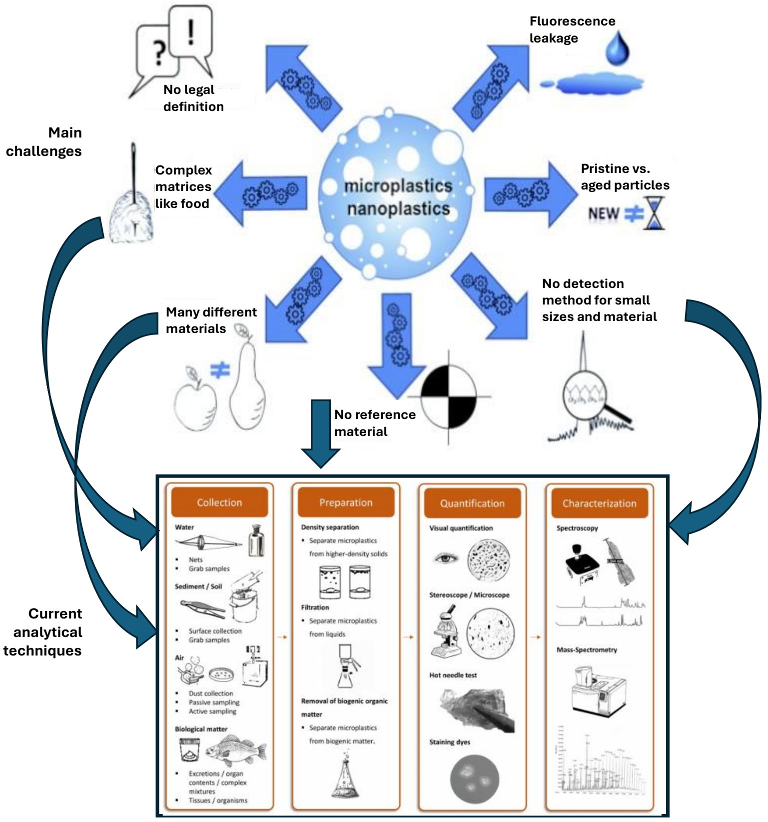

Figure 4. Current regulatory and analytical challenges on the detection and quantification of MPs in environmental matrices, alongside issues like lack of standardized protocols and regulatory frameworks. Adapted from Prata et al. (2024) [62] and Dongo et al. [63] with permission from OAE Publishing.

Adding to this complexity is the lack of universally accepted and harmonized standard operating procedures (SOPs) for sampling, sample pretreatment, extraction, identification, and quantification of MPs. This absence hampers the reproducibility and comparability of results among laboratories and studies worldwide, impairing meta-analyses and comprehensive assessments of environmental MPs [64]. Many initiatives have proposed methodological frameworks and interlaboratory comparison exercises, but consensus is still far from being achieved.

From a regulatory perspective, the landscape is poorly consolidated and fragmented. Most existing environmental policies and legislations do not explicitly address MPs as discrete contaminants, reflecting the novelty and scientific uncertainties surrounding MP occurrence and risks. To date, no internationally binding regulation sets threshold limits for MPs in environmental matrices such as wastewater effluents, soils, or biosolids. This regulatory gap leads to inconsistent approaches among countries, variability in monitoring requirements, and often a lack of enforcement mechanisms for MP control.

While the European Union has begun incorporating MP concerns into wider plastic pollution strategies, such as the EU's Plastics Strategy and the Water Framework Directive, specific legislative instruments setting quantifiable standards and risk-based criteria are still under development [65]. Similarly, agencies like the US EPA have recognized MPs as emerging contaminants, but are yet to establish concrete regulatory limits or monitoring guidelines. The lack of standards for MPs in biosolids, sludge, and agricultural soils is especially problematic given the widespread practice of land application of sewage residues containing MPs, as contamination by MPs may pose long-term ecological and health risks [66].

To address these challenges, international cooperation is essential. Harmonization of analytical protocols, establishment of reference materials, development of certified measurement techniques, and integration of MP monitoring into existing environmental surveillance frameworks are urgently needed. Furthermore, regulatory frameworks must evolve in tandem with scientific advancements, incorporating risk assessment outcomes and socio-environmental considerations to set realistic and enforceable limits. The formation of interdisciplinary working groups combining researchers, regulators, and industry stakeholders is a promising path forward to close these knowledge and governance gaps.

4. Methods for Microplastic Removal in Effluents

Effluents, particularly from WWTPs, are significant carriers of MPs into aquatic systems. Due to their small size and persistent nature, there is an increasing need for effective methods to remove MPs from effluents before they are discharged into the environment. Numerous techniques have been developed to tackle this challenge, each exhibiting different levels of effectiveness, advantages, and limitations [3]. This section reviews the most common and emerging methods currently employed or proposed for the removal of MPs from wastewater effluents.

4.1. Filtration

Filtration is one of the most commonly used methods for MP removal from effluents [67]. During the primary treatment phase of WWTPs, large particles, including MPs, are typically removed using coarse filters or screens. These filters can capture larger MPs, but their effectiveness decreases for smaller particles (less than 100 μm) due to limited pore size limitations and clogging by organic matter [68]. In more advanced treatment stages, secondary and tertiary filters with finer mesh sizes can capture smaller MPs [69]. However, despite improvements in filtration technologies, MPs under 10 μm can still pass through and enter the treated effluent. To increase efficiency, filtration may be combined with other treatment processes, such as coagulation or flocculation [70]. A major challenge is the clogging of sieves with organic matter, which reduces separation efficiency. Continuous-flow filtration systems and automated cleaning technologies have been proposed to address this issue and improve removal rates. Nevertheless, the overall effectiveness of filtration in large-scale systems remains limited by particle size and the nature of MPs [71]. Recent advances in membrane technology include the development of hybrid membranes incorporating nanomaterials, such as graphene oxide, metal–organic frameworks (MOFs), and other nanocomposites [72]. These membranes exhibit enhanced selectivity, antifouling properties, and mechanical strength, offering promising solutions for the efficient removal of even the smallest MPs and NPs [72]. However, their large-scale application remains limited by production costs and long-term stability. Magni et al. (2019) reported that a WWTP in Northern Italy, equipped with multiple treatment stages, achieved a removal efficiency of MPs of about 84% [73]. However, a considerable number of MPs were still released into freshwater, eventually contaminating soils as well. Membrane filtration systems are also used as tertiary treatment solutions, particularly for smaller plastic particles [74]. The reuse and recycling of membranes can reduce environmental impact and treatment costs, but polymeric membranes themselves can become a source of plastic waste. As a result, there is an increasing interest in developing bio-based, recyclable, and biodegradable membranes as sustainable alternatives. Talvitie et al. (2017) [75] compared various secondary treatment technologies, including membrane bioreactors (MBRs), rapid sand filtration (RSF), dissolved air flotation (DAF), and disk filters [75]. The MBRs achieved MPs removal of 99.9%, RSF 97%, DAF 95%, and disk filters between 40 and 98.5% [75]. Each method has specific limitations: RSF may require coagulants to prevent MPs from adhering to sand grains, disk filters may not retain all MPs due to pore size, and DAF is more effective for low-density plastics.

4.2. Flotation

Flotation exploits the density differences between MPs and water, allowing for MPs to be separated by attaching air bubbles to the particles, which then rise to the surface for removal [76]. This method is typically used in conjunction with coagulation or flocculation to enhance the removal of fine MPs. Flotation is effective for larger MPs and debris, but its efficiency decreases for smaller particles [77]. Chemical additives, such as surfactants or coagulants, can improve flotation efficiency by altering the surface properties of MPs, promoting their interaction with air bubbles [77]. However, the use of chemicals raises concerns about introducing additional contaminants into the treated effluent.

4.3. Chemical Coagulation

Chemical coagulation involves adding coagulants, such as aluminum sulfate (alum) or ferric chloride, to wastewater to agglomerate suspended particles, including MPs, into larger flocs for subsequent removal by sedimentation or filtration [78]. This method is effective for MPs in the 100 µm to 1 mm range, but less so for smaller particles. Coagulation can generate large volumes of sludge, requiring proper disposal or further treatment, and the long-term toxicity of coagulants to aquatic organisms must be considered. Recent studies have explored advanced coagulation techniques. Chen et al. (2020) demonstrated that composite metal calcium–aluminum coagulants performed best at high pH, while coagulation is less effective in acidic environments [79]. Misra et al. (2019) [80] developed a novel approach using magnetic nanoparticles coated with ionic liquids, enabling the easy magnetic extraction of MPs and other contaminants. This system allows for the purification of large water volumes with a minimal infrastructure, showing promise for both centralized and decentralized water treatments. Wang et al. (2019) proposed the use of TiO_2-based micromotors for innovative MP extraction. These micromotors interact with MPs through phoretic and photocatalytic mechanisms, achieving significant removal under UV light [81]. Such approaches highlight the potential of nanotechnology and advanced materials in MP removal.

4.4. Flocculation

Flocculation is widely applied in industries, such as papermaking and mineral processing, during wastewater treatment. It promotes the aggregation of suspended particles through mechanisms such as charge neutralization and polymer bridging. The effectiveness of flocculation depends on several factors, including the properties of the flocculant, the characteristics of the particles, and the conditions of the aqueous medium. If the flocculant being used consists of long molecular chains, polymer bridging will be the preferred flocculation mechanism, which involves the adsorption of high-molecular-weight polymers in an extended conformation on particle surfaces, consequently forming loops and tails that connect multiple particles together [82].

MP particles present mostly negative surface charge due to charged groups (mainly carboxylic groups) formed during plastic degradation [83]. In this context, cationic and/or cationic and hydrophobically modified polymers represent an attractive way to flocculate MPs and enhance their removal from effluents [84] (see Figure 5). Polyacrylamides are the most common cationic flocculants in water treatment applications. However, natural polyelectrolytes derived from wood wastes, modified by introducing cationic and hydrophobic groups to enhance interaction with negatively charged particles or low-charge particles, are highly attractive alternatives [85]. Magalhães et al. (2025) developed a series of cellulose derivatives which have demonstrated high potential to flocculate model polyethylene and polyethylene terephthalate MPs [84]. This work demonstrated that it is possible to fine-tune the cellulose derivative's structure, enabling the flocculation of MPs of different natures (e.g., PET, PE, and PVC, and having different degrees of charged groups on the particle surface) in effluents with different physicochemcial characteristics (different pH), obtaining high removal efficiency independently of the nature of the MPs and removal conditions. The results demonstrate superior performance in MP removal compared to commercial polyacrylamides [83]. These promising outcomes, achieved using bio-based flocculants, are particularly noteworthy given the absence of the need of an additional coagulant, which is commonly used in standard practices. For example, Li et al. (2024) explored the use of polyacrylamides to flocculate MPs in the presence of a coagulant species (polyaluminum chloride), obtaining high removal capacities (up to 95%) [86]. Although promising, the approach reported by Li et al. requires the use of a coagulant, which may hinder the reuse of the recovered MPs—for example, in composites or as fillers in bitumen. In contrast, the work by Magalhães et al. avoids this limitation due to the absence of added coagulants. Additionally, as stated in the previous sections, the coagulants used can be toxic to the environment, and their use for MP removal should therefore be avoided.

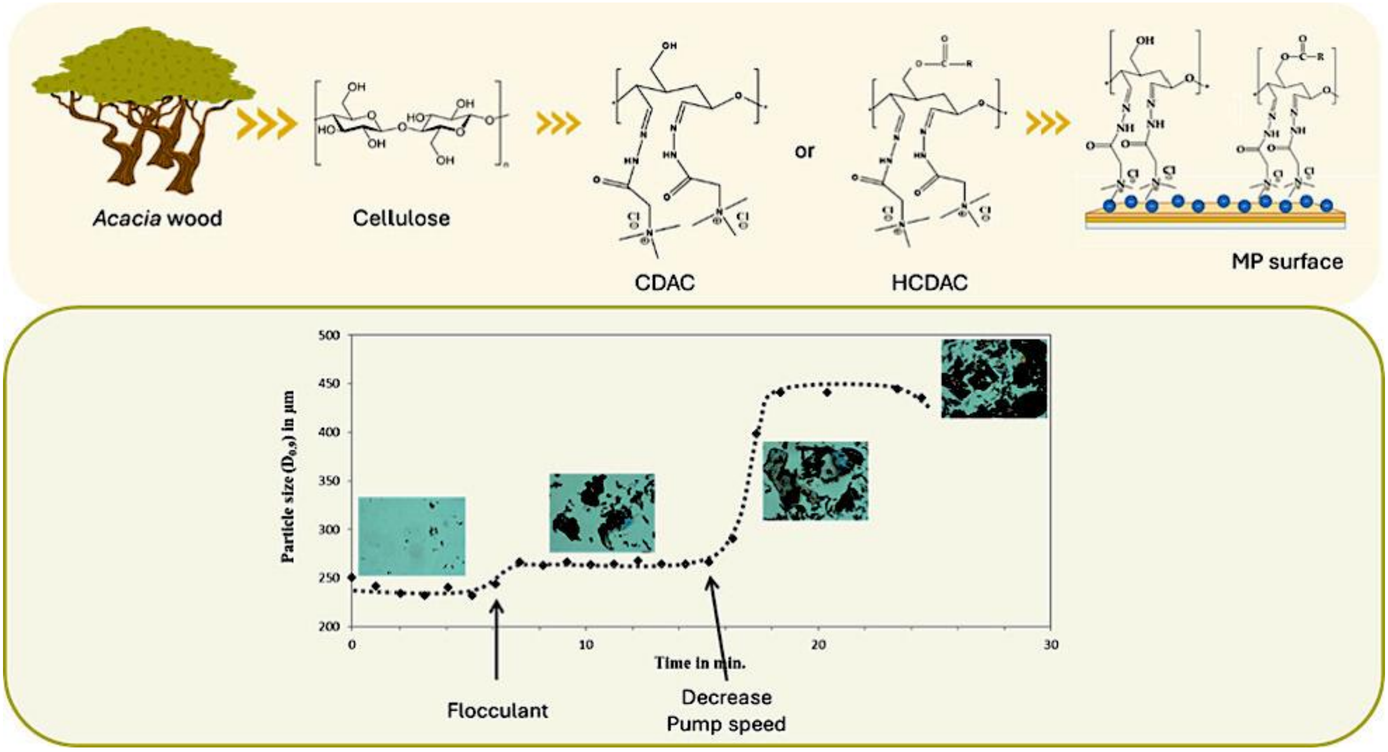

Figure 5. Synthesis of cationic bio-based flocculants derived from cellulose extracted from biomass, and the flocculation process that enhances the removal efficiency of MPs from wastewater. Taken from Magalhães et al. (2025) [84] with permission from Elsevier.

4.5. Advanced Oxidation Processes

Advanced oxidation processes (AOPs), such as ozonation, UV irradiation, and Fenton reactions, have been investigated for their ability to degrade MPs and NPs in wastewater [87]. These processes produce highly reactive species capable of breaking down polymer chains, potentially reducing MPs to less harmful byproducts [88]. However, promising, AOPs often require high-energy inputs and may generate secondary pollutants, resulting in the need for further optimization for their practical use.

Certain AOPs also couple chemical oxidation with photocatalytic effects, using catalysts such as titanium dioxide (TiO_2) or zinc oxide (ZnO) under UV light to enhance the degradation efficiency of common polymers, including polyethylene (PE) and polystyrene (PS) [89]. These processes have demonstrated promising results in reducing microplastic size and concentration in controlled laboratory settings.

However, despite their potential, the practical application of AOPs faces several critical challenges. One of the main limitations is the high energy demand, particularly associated with UV-based processes that require intense light sources and controlled operational conditions, such as pH and temperature, to optimize radical generation [90]. Such energy requirements raise concerns regarding the economic feasibility of AOPs for large-scale WWTPs with high flow rates.

Another important issue is the formation of secondary pollutants during treatment, including partial oxidation byproducts and fragmented NPs that may exhibit increased mobility and toxicity compared to the original MPs [91,92]. Under real-world operational conditions, complete mineralization of plastics into carbon dioxide and water is seldom achieved, highlighting the need for further optimization to reduce the formation of undesirable byproducts.

The efficiency of AOPs is also impacted by the complexity of wastewater matrices, where the presence of natural organic matter, suspended solids, and inorganic ions can act as radical scavengers, reducing the availability of reactive species for MPs degradation [93]. Therefore, AOPs require pre-treatment or combined treatment processes to enhance overall removal performance.

Recent advances aim to address these limitations through the development of heterogeneous photocatalysts that operate under visible light, the integration of AOPs with electrochemical methods to sustain radical production, and the design of optimized reactor configurations to improve contact between MPs and reactive species [94]. Moreover, combining AOPs with physical separation or biological treatment methods in hybrid systems is a promising strategy to achieve higher removal efficiencies while minimizing energy consumption and secondary pollution.

In conclusion, while AOPs offer a chemically robust approach for the degradation of MPs in wastewater, their scalability and sustainability depend on overcoming challenges related to energy use, secondary pollutant formation, and matrix interferences. Continued research into catalyst development, process intensification, and system integration is essential to achieve the practical application of AOPs for microplastic mitigation in effluents.

4.6. Bioremediation

Bioremediation uses microorganisms such as bacteria, fungi, and algae to degrade or adsorb MPs [95]. Certain microbial species can break down synthetic polymers or adsorb MPs onto their surfaces, reducing their concentration in treated effluent. Notably, bacteria such as *Ideonella sakaiensis*, known for PET degradation via PETase enzymes [96], *Pseudomonas aeruginosa* [97], *Rhodococcus* sp. [98], and *Bacillus* [99], as well as fungi like *Aspergillus niger* [100], *Penicillium brevicompactum* [101], and *Phanerochaete chrysosporium* [102], have demonstrated capabilities to biodegrade many types of plastics or aid in MP removal through adsorption. This eco-friendly and potentially cost-effective method is still under investigation, as many MPs are resistant to biodegradation, especially those from non-biodegradable plastics. The diversity of MPs types and the potential for harmful microbial byproducts present additional challenges. Microalgae have shown potential as biofilters for MP removal. Lagarde et al. (2016) demonstrated that marine algae, such as Fucus vesiculosus, can entrap MPs, achieving removal efficiencies up to 94.5% in some cases [103]. The electrostatic charge on algal surfaces plays a key role in MP adsorption. However, the presence of biofilms on MPs can reduce removal efficiency, as shown by Sturm et al. (2022), due to changes in surface chemistry [104]. Simulating environmental exposure is therefore crucial when evaluating bioremediation strategies.

4.7. Integrated and Hybrid Systems

Integrated treatment systems that combine physical, chemical, and biological processes are increasingly being explored to maximize MP removal efficiency. For example, coupling membrane filtration with coagulation–flocculation or bioremediation can address a broader range of particle sizes and compositions while minimizing operational costs and environmental impacts. The integration of advanced materials, such as nanocomposites or catalytic membranes, further enhances the versatility and effectiveness of these systems; see Figure 6.

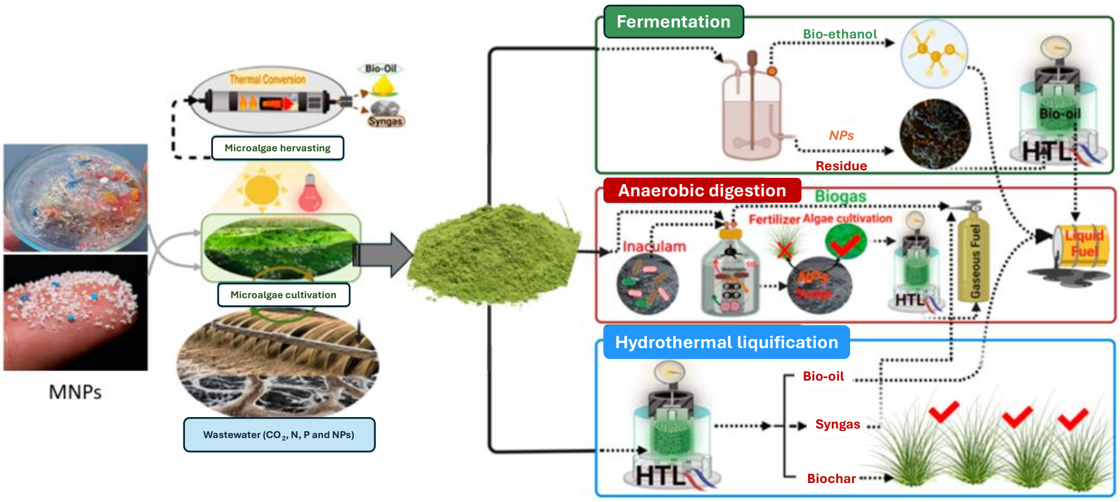

Figure 6. Integrated treatment approach combining microalgae cultivation with MP and NP removal in wastewater. Wastewater nutrients are used for algae growth, adsorbing micro-/nanoplastics, leading to the subsequent conversion of algal biomass into biofuels via hydrothermal liquefaction. Taken from Abomohra et al. (2022) [105] with permission from MDPI.

For instance, coupling membrane filtration techniques (e.g., microfiltration, ultrafiltration) with coagulation–flocculation allows for the effective capture of a wide size spectrum of MPs, from large fragments to fine particles and even some smaller NPs, by aggregating dispersed particles into larger flocs that are more easily retained by membranes [106]. This reduces membrane fouling and extends operational lifespan, while improving overall removal rates. Additionally, these physical-chemical combinations can be enhanced by employing advanced materials, such as nanocomposite membranes imbued with antimicrobial or catalytic properties that degrade MPs or prevent biofouling [107].

On the biological front, bioremediation strategies utilizing microorganisms or microalgae can be integrated downstream or upstream of physicochemical treatments [91]. Microalgae can not only adsorb and bioaccumulate MPs, but also valorize wastewater nutrients for biomass growth. This biomass can subsequently be converted to bioenergy (e.g., biofuels via hydrothermal liquefaction, HTL), simultaneously achieving resource recovery and pollution mitigation, as exemplified in Figure 6 from Abomohra et al. (2022) [105]. The incorporation of MP/NP studies into these systems further allows for the optimization of operational parameters to maximize removal while minimizing environmental release.

Hybrid systems also encompass AOPs coupled with biological treatments, where the partial chemical degradation of MPs eases biodegradability and enhances microbial assimilation. Electrochemical treatments combined with membrane filtration, often labeled electro-membrane processes, represent another emergent hybrid avenue, offering simultaneous physical separation and catalytic degradation under electrical stimulation [108].

Despite these advantages, integrated approaches face critical challenges. The complexity of combining multiple unit operations increases capital and operational costs, process control requirements, and can produce secondary pollutants from reagents or incomplete degradation byproducts. Scalability and adaptation to variable wastewater characteristics remain obstacles. Furthermore, a comprehensive assessment of the fate of degraded MPs and their byproducts within integrated systems is still incipient, necessitating more robust analytical frameworks.

Research into smart materials, such as stimuli-responsive membranes or multifunctional adsorbents capable of selective MP capture, is expanding the horizon of integrated technologies. Coupled with process intensification strategies and digital process monitoring (e.g., sensor integration, AI-driven control), hybrid systems promise adaptable, efficient, and sustainable MP removal solutions aligned with circular economy principles.

4.8. Limitations and Challenges

While these methods have shown to be promising, several challenges remain for the large-scale application of MP removal technologies. The wide variety of MP types, sizes, and compositions renders the development of universal removal methods difficult. The high costs and energy requirements of advanced techniques, such as electrochemical treatments and AOPs, may limit scalability. The risk of secondary pollution, such as the release of harmful chemicals or byproducts, must also be managed. The absence of standardized protocols for assessing MP removal efficiency poses challenges when comparing results across studies and for regulatory development. A particularly critical issue is the effective removal of NPs, which remain difficult to detect and eliminate with current technologies. Their small size, high mobility, and increased surface area raise concerns about their environmental and health impacts, underscoring the need for further research into detection and removal strategies specifically targeting NPs. In summary, while conventional and emerging methods for MP removal from effluents have demonstrated different degrees of success, several challenges persist, particularly regarding the removal of NPs, scalability, cost-effectiveness, and potential secondary pollution. Future research should focus on the development of integrated, energy-efficient, and sustainable treatment systems, as well as on the establishment of standardized protocols for monitoring and evaluating MP removal in real-world settings.

5. Methods for Microplastic Removal in Soils

The contamination of soils with MPs is an emerging environmental issue with significant implications for soil health, agricultural productivity, and ecosystem functioning [35]. Unlike effluent systems, where MPs can be removed through water-based treatments, the removal of MPs from soils presents unique challenges due to the heterogeneity of soil matrices, the diversity of plastic types, and the complex interactions between MPs and soil particles. A variety of methods have been proposed or applied for the remediation of MPs in soils, each with distinct advantages and limitations depending on the characteristics of both the soil and the MPs present. This section reviews the most common and emerging techniques for the removal of MPs from soils, including physical, chemical, biological, and hybrid approaches.

5.1. Mechanical Separation

Mechanical separation remains one of the most straightforward approaches for extracting MPs from soils, particularly when MPs are visible or concentrated in specific areas. Techniques, such as sieving and flotation, are commonly employed:

Sieving utilizes meshes of different sizes to separate larger MPs from soil particles. While effective for MPs above 0.5 mm, sieving is less efficient for smaller particles and does not recover MPs embedded within soil aggregates or organic matter [109].

Flotation exploits density differences by introducing high-density salt solutions (e.g., NaCl, NaI, $ZnCl_2$) to soil, causing lighter MPs to float and enabling their collection. The method is most effective for buoyant MPs, but can be limited by soil type, MP density, and the chemical composition of the flotation solution. Additionally, flotation is less effective for small or irregularly shaped MPs and may require further purification steps [110]. Also, it is not possible to apply this technique in situ, and the contaminated soil will have to be removed to landfills.

Mechanical approaches are practical for laboratory-scale studies and soils with high concentrations of large MPs, such as those impacted by sewage sludge or plastic mulch. However, their effectiveness decreases in heterogeneous soils and for MPs at the micro- and nano-scale.

5.2. Density Separation

Density separation is a widely used chemical-physical technique that exploits the differences in density between MPs and soil minerals [111]. By mixing soil samples with a high-density solution, heavier soil particles sink while lighter MPs float to the surface, allowing for their subsequent collection and filtration. This method has proven to be effective for extracting MPs lighter than most soil minerals and is applicable across different soil types [111]. However, its efficiency can be compromised in soils with high organic matter content, which may interfere with separation. Moreover, density separation is labor-intensive, time-consuming, and generates waste solutions that require proper disposal, posing environmental and logistical challenges for large-scale applications. Recent research is focused on optimizing solution composition and integrating pre-treatment steps, such as oxidation of organic matter, to enhance recovery rates and minimize environmental impact [112].

5.3. Bioremediation

Bioremediation leverages the natural potential of microorganisms to degrade or immobilize MPs in soils. Certain bacteria and fungi have demonstrated the ability to produce enzymes (e.g., PETase, laccase, cutinase) capable of breaking down synthetic polymers, such as polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET) [113]. Microbial degradation offers a sustainable and eco-friendly alternative to traditional methods, although it is generally slow and more effective for biodegradable plastics. Non-biodegradable MPs remain largely resistant to microbial attack. In addition to enzymatic degradation, microorganisms may adsorb or sequester MPs within biofilms, reducing their mobility and bioavailability [114]. While promising, these processes are still under investigation, and their efficiency depends on soil conditions, microbial populations that may require bioaugmentation by adding non-native microbes to the soil, and the type of plastics present. Scaling bioremediation from laboratory to field remains a significant challenge, and further research is needed to enhance degradation rates and optimize the required conditions in the soil.

Rahman et al. (2023), using bioaugmentation with PET-degrading bacteria, documented reductions of up to 20% in MP volume after 12 weeks, whereas soils not treated with microorganisms only exhibited a 3–5% reduction over the same period [115]. In trials employing fungi such as Phanerochaete, degradation rates for polystyrene in soil ranged from 10% to 22% after two months, depending on nutrient supplementation [116]. While engineered consortia and enzyme-assisted approaches further increased removal rates, the overall efficiency seldom exceeded 30% in three months under realistic field conditions. This contrasts with conventional effluent treatment systems, which typically remove 50–90% of microplastics above 100 µm in short times, but are less effective (10–20%) for smaller MPs [117].

5.4. Phytoremediation

Phytoremediation, involving the use of plants to remediate contaminated soils, is also being explored as a potential strategy for MP removal, particularly for smaller particles not easily addressed by mechanical methods [118,119]. Certain plant species with extensive root systems may adsorb or bind MPs from the soil matrix, either incorporating them into plant tissues or retaining them on root surfaces [120]. Examples include agricultural crops such as maize (*Zea mays*) [121], rice (*Oryza sativa*) [122], and wheat (*Triticum aestivum*) [123], which possess extensive fibrous root systems capable of interacting with soil-bound MPs. However, the efficiency of phytoremediation for MPs is still under investigation, and concerns remain regarding the potential transfer of MPs into the food chain [119]. In spite of that, plants can help stabilize soils, reduce erosion, and limit the spread of MPs by binding them to roots and organic matter. While environmentally friendly and cost-effective, the long time required for effective removal and the long-term effectiveness and ecological safety of phytoremediation for MP removal require further study.

Recent research highlights three major phytoremediation mechanisms for micro-/nanoplastics: phytoaccumulation, phytostabilization, and phytofiltration [124]. Phytoaccumulation involves roots absorbing and accumulating nanoplastics into plant tissues, reducing environmental load [125]. For instance, studies have demonstrated uptake and transport of polystyrene particles from roots to shoots in crops like *Triticum aestivum*, showing feasibility for the removal of submicron plastics [126]. Phytostabilization refers to the adsorption or immobilization of MPs on root surfaces, limiting their mobility and bioavailability. Phytofiltration describes plants intercepting plastic particles from water or air flows, acting as physical barriers to their spread. Additionally, root exudates and rhizosphere microorganisms may enhance plastic degradation and help plants tolerate plastic exposure. These synergies position phytoremediation as a sustainable approach complementary to other remediation technologies [127].

Nonetheless, challenges remain due to the non-permanence of plastic immobilization on plant surfaces, requiring the timely harvesting and recycling of hyperaccumulator plants to avoid remobilization or entry of MPs into food chains. Careful selection of species outside common animal diets is recommended to mitigate ecological risks. Combining phytoremediation with microbial degradation or chemical methods is promising to improve the efficiency and field applicability of this strategy.

Plants also contribute to soil stabilization and erosion control, limiting microplastic dispersal by physically binding them to the organic-rich rhizosphere [128]. While requiring longer periods for effective remediation compared to conventional treatments, phytoremediation offers a cost-effective, environmentally friendly strategy with high sustainability potential, especially targeting nanoplastics and submicron plastics that are otherwise difficult to capture [129].

5.5. Chemical and Enzymatic Approaches

Chemical and enzymatic methods for MP removal from soils are still in early stages, but offer potential for targeted degradation or transformation of plastic particles [130]. Enzymes, such as PETase and cutinase, have shown promise in laboratory studies for breaking down specific polymers, but challenges remain in delivering these enzymes effectively into soil environments and achieving complete mineralization; see Figure 7 [130,131]. Solvent treatments may also be used to dissolve or fragment MPs, facilitating their extraction, although concerns about solvent toxicity, environmental safety, and cost limit their practical application. Advances in biotechnology, including engineered enzymes and microbial consortia, may enhance the feasibility of these approaches in the future.

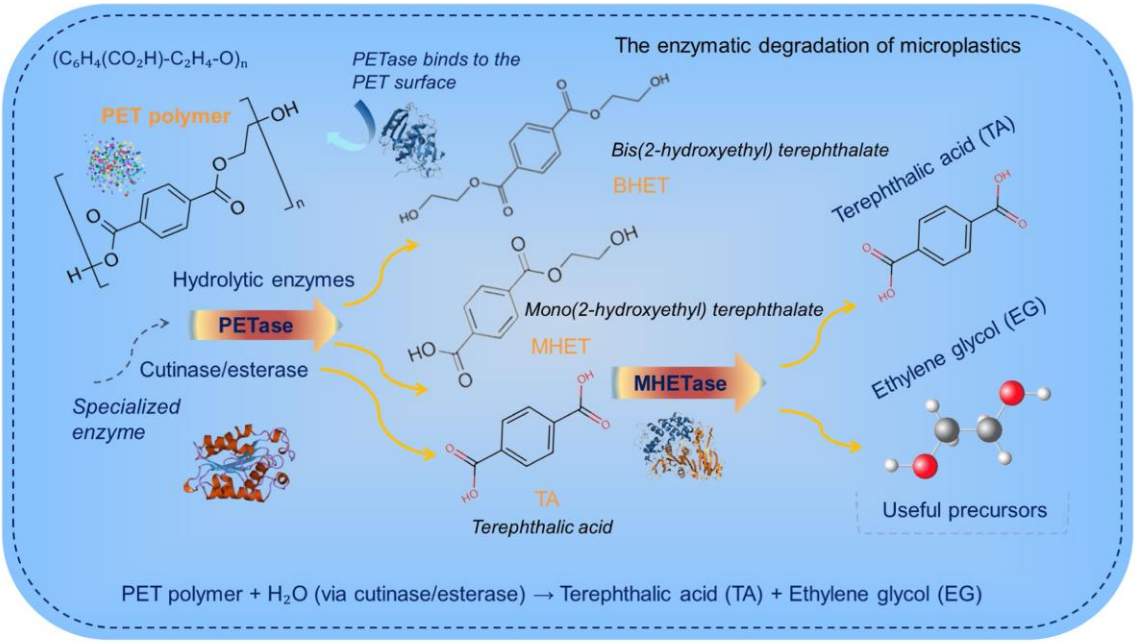

Figure 7. Enzymatic degradation pathway of polyethylene terephthalate (PET) microplastics by specific enzymes such as PETase and cutinase to form smaller and non-toxic molecules. Reprinted from Nguyen et al. (2025) [131] with permission from Elsevier.

5.6. Integrated and Hybrid Approaches

Given the complexity and diversity of MPs in soils, integrated and hybrid methods are increasingly being explored (Figure 8). Combining physical (e.g., mechanical separation), chemical (e.g., density separation), and biological (e.g., bioremediation or phytoremediation) techniques can improve overall removal efficiency and address a wider range of particle types and sizes. For instance, pre-treating soils with density separation followed by microbial or enzymatic degradation may enhance the breakdown of residual MPs. Coupling phytoremediation with microbial inoculation can increase MP immobilization and degradation in situ.

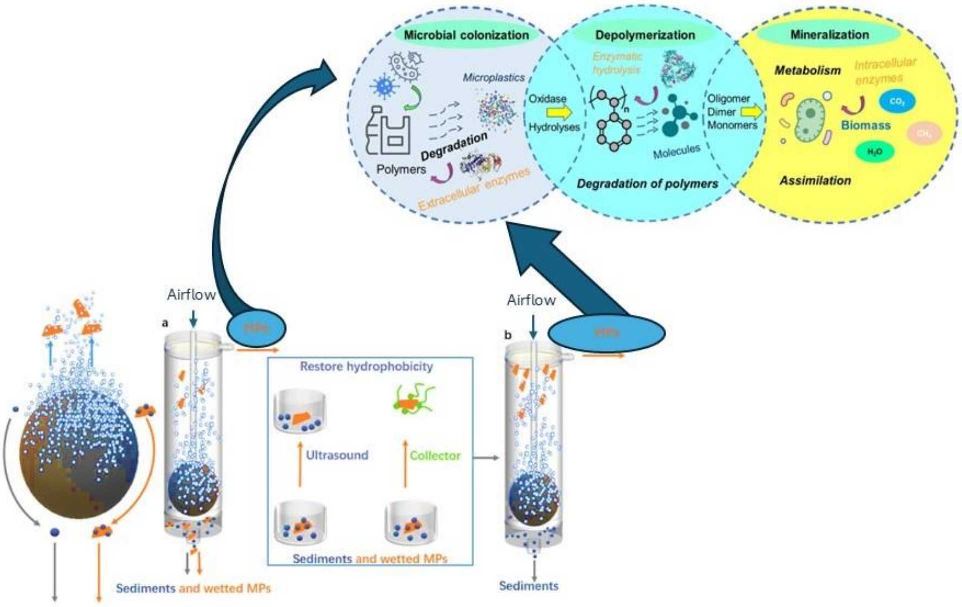

Figure 8. Hybrid remediation strategy for MPs in soils, combining flotation for physical isolation with subsequent biological treatment for enhanced degradation. Adapted from Nguyen et al. (2025) [131] and Jiang et al. (2022) [132] with permission from Elsevier.

For example, it is known that MPs can change the pH, water-holding capacity, and oxygenation, among other properties, of soils, which impacts their microbial activity and, therefore, their capacity to degrade MPs into small and non-toxic molecules. The isolation or concentration of MPs, achieved by applying a physical method such as flotation, can reduce the impact MPs have on soil characteristics and render the degradation of MPs by microorganisms more favorable [131].

5.7. Limitations and Challenges

Despite recent progresses, several challenges persist for the effective removal of MPs from soils. The diversity of MPs types, sizes, and polymer composition renders the development of universal remediation methods difficult. Many MPs, especially those made from conventional plastics, are highly resistant to degradation. Most current methods are labor-intensive, costly, and difficult to scale for large contaminated areas. Biological approaches, while sustainable, often require long timeframes and optimal conditions. Additionally, there is a lack of standardized protocols for MP extraction and quantification in soils, hindering the comparison of results across studies and the development of regulatory guidelines. Future research should focus on developing more efficient, scalable, and environmentally friendly remediation technologies, advancing biotechnological solutions such as engineered enzymes and microbial consortia, integrating multiple removal strategies for synergistic effects, and establishing standardized methods for MP detection, extraction, and monitoring. Addressing these challenges will be essential for mitigating the long-term environmental and health impacts of microplastic contamination in soils.

6. Overview of Microplastic Removal Processes

Despite significant advances in the development of MP removal technologies, several persistent challenges hinder the implementation of effective, sustainable, and scalable solutions. These challenges are multifaceted, involving technical limitations, economic constraints, and environmental and health considerations, as evidenced by case studies from research studies and on-site practices. Table 1 summarizes the main MP removal methods, highlighting their principles, advantages, and limitations, and illustrating how they relate to the challenges discussed in this section.

Table 1. Summary of main MP removal and separation methods, principles, advantages, limitations, and typical applications.

Method	Principle/Process	Advantages	Removal Efficiency	Limitations	Main Applications	Technology Readiness Level (TRL)	Ref.
Filtration	Physical size exclusion	Simple, widely implemented	40–99%	Less effective for <10 µm MPs; clogging	Wastewater treatment plants	9 (fully implemented in wastewater plants)	[73,75]
Flotation	Density-based separation	Effective for larger MPs	~95%	Use of chemicals; less effective for small/irregular MPs (for 1 to 10 µm MPs, the removal is below 80%)	Water and wastewater treatment	7–8 (operational, semi-commercial)	[77]
Chemical coagulation	Aggregation via coagulants	Removes fine particles	~95%	MPs above 1 µm; sludge generation; reagent cost; toxicity	Water and wastewater treatment	8–9 (widely applied in municipal/industrial)	[80,81]

Table 1. *Cont.*

Method	Principle/ Process	Advantages	Removal Efficiency	Limitations	Main Applications	Technology Readiness Level (TRL)	Ref.
Advanced oxidation processes	Chemical oxidation (e.g., ozonation, UV, Fenton)	Degradation of MPs and nanoplastics	~95%	MPs above 1 µm; high energy/cost; possible secondary pollution	Industrial effluents	6–7 (pilot set-ups, growing in industry)	[81]
Biormeediation	Microbial/ enzymatic degradation or adsorption	Sustainable, eco-friendly	94.5%	MPs from 400 to 1000 µm; slow; limited to certain polymers	Soils, wastewater	4–6 (laboratory to early field trials)	[103]
Density Separation (Soil)	Separation using high-density salt solution	Good for low-density MPs	-	Labor-intensive; waste solution	Soil and sediment analysis	6 (used for research, limited field tests)	[29]
Phytoremediation	Uptake/ immobilization by plants	Low-cost, environmentally friendly	-	Limited efficiency; long time needed; risk of food chain transfer	Soil stabilization	4–6 (mainly lab experiments, some field cases)	[119]
Integrated/ Hybrid Systems	Combination of above methods	Higher efficiency, broader scope	-	Increased complexity, cost	Advanced wastewater/soil treatment	5–7 (demonstrated, not fully mature commercially)	[79]

TRL 4–6: Technology validated in lab/field early-stage trials. TRL 7–9: Pilot set-ups, demonstration plants, commercial/operational maturity.

6.1. Particle Size and Diversity

One of the most critical barriers to efficient MP removal is the wide range of particle sizes and morphologies present in environmental matrices. MPs can range from visible fragments and fibers to sub-micron and even nanoplastic particles, with smaller particles (<1 µm) being especially difficult to detect and remove using conventional filtration or sedimentation methods [133]. For example, a study on a garden soil demonstrated the presence of both large (5 mm–100 µm) and small (<100 µm) MPs, highlighting the challenge of recovering the smallest fractions, even when using tuned laboratory techniques [134]. This diversity is further enhanced by different polymers types, densities, and surface chemistries which influence MPs' behavior and interactions in different removal technologies.

6.2. Cost, Reusability, and Scalability

Economic factors play a central role in the adoption of MP removal solutions. Advanced technologies such as ultrafiltration, membrane bioreactors, and nanotechnology-based processes have demonstrated high removal efficiencies in controlled studies, but their high energy consumption, expensive reagents, and maintenance costs limit their scalability for large-scale or municipal applications [135]. For instance, while ultrafiltration has proven to be more effective than conventional filtration for removing MPs from water, as shown in comparative studies, it requires significant investment in infrastructure and high operational costs [136]. In Brazil, most WWTPs still rely on conventional methods, which are less effective for MP removal due to budgetary and technical constraints [137]. Furthermore, the durability and reusability of membranes and filters remains a concern, as fouling and material degradation can reduce performance and increase waste generation over time.

6.3. Environmental and Health Risks

Some removal techniques, particularly those involving chemical or solvent treatments, may inadvertently introduce new environmental risks. For example, the use of coagulants or surfactants can lead to the formation of toxic byproducts or residual chemicals in treated water, potentially affecting aquatic organisms and ecosystem health [138]. Additionally, the degradation of MPs during treatment processes may generate even smaller particles or NPs, which pose higher risks due to their increased mobility and potential for bioaccumulation. The risk of MPs entering the food chain through plant uptake or animal ingestion remains a significant concern, as demonstrated by studies on the fate of MPs in agricultural soils irrigated with treated effluent or amended with sewage sludge [139]. In Europe and North America, hundreds of thousands of tons of MPs are introduced into soils annually via sewage sludge, raising questions about long-term soil health and food safety [140].

6.4. Lack of Standardization and Monitoring

The absence of standardized protocols for sampling, extraction, and quantification of MPs in different environmental matrices makes the assessment of removal efficiency and the comparison of results across studies [141]. For example, a study using Raman spectroscopy to identify MPs in soil highlighted the difficulty of distinguishing plastics from organic matter, especially for small particles embedded in complex matrices [142]. This lack of harmonization also inhibits regulatory development and the establishment of guidelines for environmental protection, making it challenging to set benchmarks for remediation success or to monitor progress over time.

7. Microplastic Characterization

The characterization of MPs involves both physical and chemical analyses, which are essential for understanding their environmental behavior, sources, and impacts, as well as for developing effective remediation strategies. Physical characterization primarily focuses on the size distribution, shape, and color of MPs, while chemical characterization aims to identify the polymer composition and surface properties through different analytical methods.

Physical Characterization

Physical analysis generally begins with visual or microscopic examination to determine size ranges and morphologies such as fragments, fibers, or spheres. Visual identification using optical microscopy is straightforward, but is limited in reliability, as non-plastic particles like cellulose or organic matter may be misclassified as MPs without further verification [143]. Scanning Electron Microscopy (SEM) offers high-resolution surface imaging, enabling detailed differentiation between particles based on morphology and texture [144]. However, SEM does not provide compositional information, and its labor-intensive sample preparation (cleaning, drying, and conductive coating) may alter or damage MPs.

Chemical Characterization

Chemical characterization methods are divided into non-destructive and destructive approaches [145]. Non-destructive techniques, notably Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy, are widely used to identify polymer types by measuring vibrational spectra unique to chemical bonds in plastic materials [146]. FTIR analyzes infrared light absorption, often employing micro-ATR-FTIR coupled with microscopy for smaller MPs and fibers [147]. However, complexities such as fiber heterogeneity, copolymers, and mixtures of synthetic and natural materials can hinder spectral interpretation. Raman spectroscopy utilizes monochromatic laser light to induce characteristic molecular vibrations, providing complementary polymer identification with higher spatial resolution, but it can be affected by fluorescence interference [148].

Destructive methods such as pyrolysis gas chromatography–mass spectrometry (Pyro-GC-MS) thermally decompose MPs to analyze the resulting gases, offering sensitive chemical composition analysis for single particles or bulk samples [149]. Despite their detailed compositional output and ability to handle complex heterogeneous matrices, these methods do not provide information on particle count, size, or shape, and require destruction of the samples. Related thermal techniques, such as thermo-extraction coupled with GC-MS, allow for the analysis of larger sample masses, improving representativeness in environmental contexts. Liquid chromatography methods also characterize MPs chemically, but demand considerable sample amounts and are destructive [150].

Advances and Challenges

MP analysis generally requires extensive sample preparation, including matrix digestion, extraction, separation, and concentration—processes that are often time-consuming and technically demanding. Recently, fluorescence microscopy has gained attention as a rapid high-resolution tool for MP detection by employing selective fluorescent dyes [151]. These dyes interact variably with different polymer types, generating distinct fluorescence signatures that can assist in identifying MPs based on chemical composition [152].

Overall, while multiple methods exist for MP characterization, challenges remain due to the heterogeneity of MPs in size, shape, and polymer type, as well as the presence of complex environmental matrices. The development and standardization of reliable, sensitive, and high-throughput analytical techniques are critical to improving the detection, quantification, and understanding of MP pollution across diverse ecosystems.

8. Conclusions

MP contamination has emerged as a pervasive and persistent threat to both terrestrial and aquatic ecosystems, with far-reaching implications for environmental and human health. The increasing awareness of the risks posed by MPs has driven substantial research efforts toward the development and optimization of diverse removal strategies. While notable progress has been achieved, significant challenges remain, particularly regarding the effective removal of small and heterogeneous MP particles, the economic and operational feasibility of advanced technologies, and the absence of standardized protocols for detection, quantification, and remediation.

Recent advances in electrochemical methods, nanotechnology, and bio-based flocculation have shown considerable promise for enhancing MP removal efficiency. However, these emerging techniques require further research to address issues of scalability, cost-effectiveness, and potential secondary impacts. The complexity of MP pollution highlights the necessity of integrated approaches that combine technological innovation with biological solutions, policy interventions, and robust waste management practices.

In the future, a comprehensive and multi-faceted strategy will be essential to mitigate the impacts of MPs on ecosystems and human well-being. This strategy should include the continued development of advanced removal technologies, the implementation of improved waste management and plastic reduction initiatives, increased public awareness, and the establishment of stricter regulatory frameworks. International collaboration and the harmonization of analytical and remediation protocols will also be critical for addressing the global issue of MP pollution.

Moreover, future research priorities must focus on the standardization of methodologies to ensure consistent and comparable results across studies, long-term field-scale experiments to validate laboratory findings and assess environmental impacts, and the integration of biological with physicochemical methods to optimize removal efficacy and sustainability. Additionally, addressing the economic and operational barriers associated with emerging technologies will facilitate their practical implementation.

In summary, only through coordinated efforts that bridge scientific, technological, regulatory, and societal domains will it be possible to effectively confront the microplastic pollution crisis and safeguard environmental and public health for future generations.

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