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REVIEW ARTICLE

A Comprehensive Review of Microplastic Pollution and its Environmental Fate, Ecological Consequences, Detection Technologies, Remediation, and Governance

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Abstract

Primary particles are intentionally produced in the micro-size range, whereas secondary particles are generated through the fragmentation and weathering of larger plastic particles. Both forms are common pollutants in aquatic, terrestrial, and atmospheric environments. Microplastic sources include direct emissions, in situ degradation of plastic litter, runoff, waste water discharge, riverine transport, biosolid application, plastic mulch used in agriculture, long- range transport and remote deposition. Photodegradation, chemical oxidation, and microbial or enzymatic degradation influence microplastic persistence, whereas sedimentation-resuspension dynamics and pollutant adsorption affect transport and bioavailability. Remediation approaches include physical removal, chemical treatments such as coagulation-flocculation and advanced oxidation, biological and enzymatic degradation, bioaugmentation, engineered microbes, photocatalysis, electrochemical treatment and sensing, magnetic nanorobots, and hybrid nanoparticles, some of which can remove contamination by >90% within minutes. However, some problems need to be addressed before, such as the scalability cost, selectivity for various polymers and matrices and secondary pollution, by -product toxicity test and field validation. Improvements in FTIR, Raman spectroscopy, hyperspectral imaging and machine learning have brought the ability of identification down to the scale of approximately 100nm, but detection is limited by non-standard sampling and experimental design. The review discusses the current knowledge regarding the sources, distribution, fate and effects of microplastics, their detection and remediation technologies, socioeconomic and policy challenges in managing microplastics. It also highlights key mechanisms, trends and gaps that impede effective microplastic management.

Keywords: Microplastics, Photodegradation, Remediation, Wastewater discharge, Raman spectroscopy, Secondary pollution, Bioavailability.

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1. Introduction

The microplastic pollution is found in aquatic, terrestrial and atmospheric environments, where plastic particles are defined as being smaller than 5 mm. Surface runoff, atmospheric deposition wastewater discharge, riverine transport, biosolid application, agricultural plastics degradation are the sources for the introduction of microplastics into the environment. They can be distributed by human activity and environmental processes such as long-range atmospheric transport, sedimentation, and resuspension. The regions where the coasts are urbanized, the river mouths and regions of high plastic use are commonly cited as potential accumulation areas. The principal analytical stages involved in microplastic assessment, including matrix-specific sampling, particle extraction, identification, and quantification in water, sediment, and biological samples, are schematically illustrated in Figure 1.

1.1. Environmental perspective on microplastics

Microplastics can be primary (smaller particles intentionally created or produced during manufacturing of the product) or secondary (smaller particles generated by physical, chemical or biological degradation and weathering of

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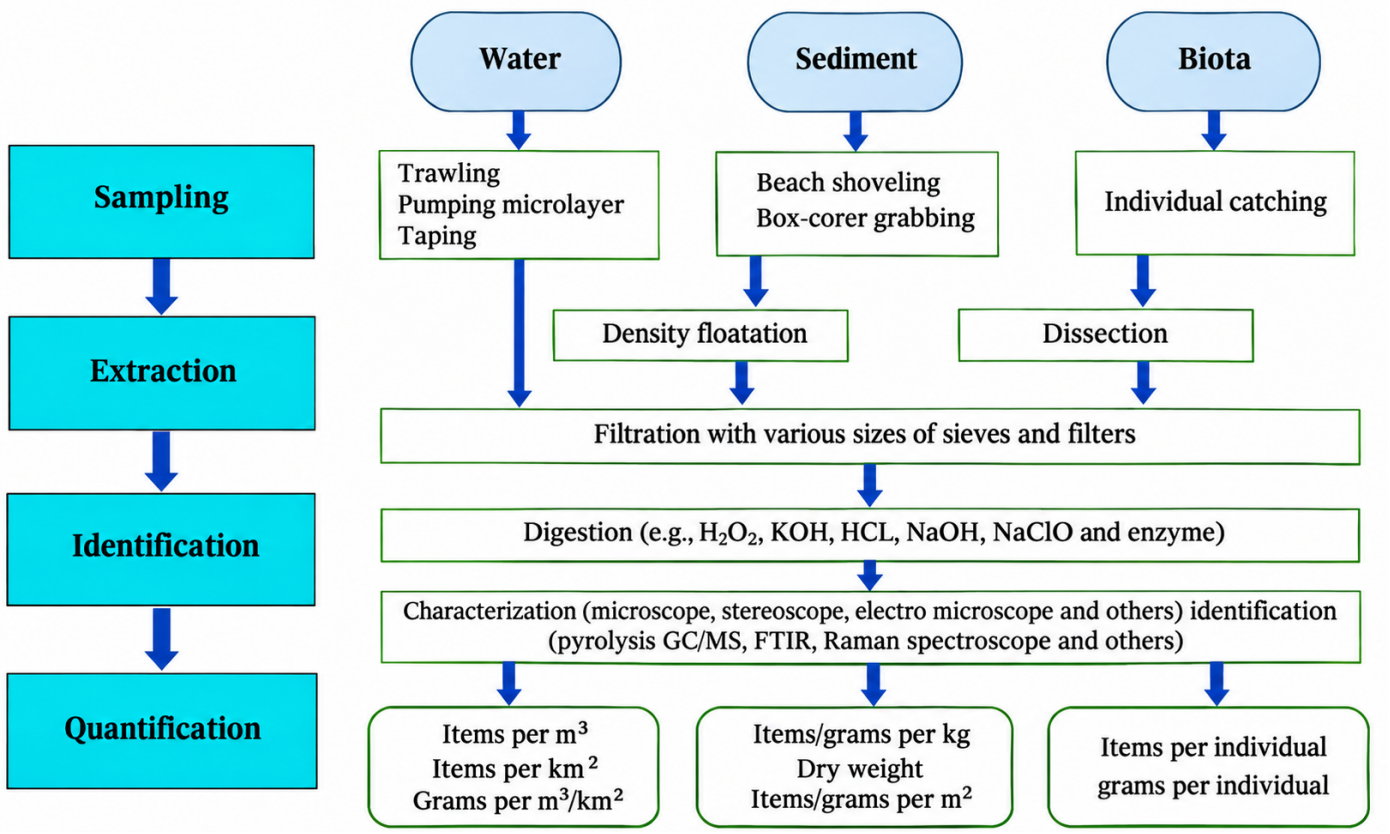


Figure 1: Schematic representation of microplastic sampling, extraction, identification, and quantification in water, sediment, and biota samples.

larger plastic materials) [1], [2]. These can enter the environment directly, by degradation of larger plastics, through atmospheric deposition. Microplastic pollution into aquatic systems is primarily from wastewater discharge, surface run-off and riverine transport. The major contaminants to terrestrial soils are biosolids, agriculture runoff and decomposition of plastic mulch. The agricultural microplastic contamination can cause impact on soil properties, crop growth, farm animals, and food safety, which makes mitigation and adaptation strategies important to agricultural systems [3]. Geographic hotspots are generally associated with high human activity such as river mouths, coastal areas, production areas of plastics. Pollutant levels typically decline with increased distance from these sources, but can be transported to distant and relatively new locations.

The other is wind wash, where microplastics can be carried through the air to the terrestrial and aquatic ecosystems ,can be widely distributed and exposed [2].The distribution of micro-plastics in aquatic ecosystems can be explained by sedimentation and resuspension, this is an important consideration in assessing potential exposure to pelagic and benthic organisms.The issue of microplastic pollution is also investigated in sensitive ecosystems like coral reefs, where pollution level and ecological risk is an important factor to monitor and to conserve the environment [4]. In plant, interactions between microplastic, soil properties and growth are also important to understand, as well as its environmental effects [5].

It is also important to understand the sources, distribution, ecological impacts and monitoring requirements of microplastics in aquatic environments to ensure effective management of microplastic pollution, as highlighted in the regional reviews [6]. Microplastics can have an ecotoxicological effect on marine and fresh water organisms. The impacts of these on the digestive tract can include obstruction, inflammation, altered feeding habits and reduced reproductive abilities, with cascading effects within populations [7]. Micro-plastics can be ingested and bioaccumulated by organisms, and there is trophic transfer leading to biomagnification in higher order predators such as humans. Microplastics may also be able to hold onto toxicants, such as persistent organic pollutants and heavy metals, which could cause additional harm to the environment [2], [8]. The effects of these impacts can include reduced biodiversity, ecosystem functioning such as nutrient cycling and energy flow. Micro-plastics changes the structure of the habitat and thus influence the composition of the microbial communities that are crucial for the resilience of the ecosystem [9]. The characteristics of microplastics can also differ between amphibian larvae of different species, which can be related to the species-specific ecology and biological and environmental factors should also be taken into account in ecological assessments [10].

High exposure to microplastics on Dreissena species have also been investigated, which shows a negative effect on the health and survival of the organism ,may lead to the use of freshwater mussels for freshwater pollution monitoring[11]. Plastic pollution is evident in birds' nests

and could be used as environmental indicators to monitor plastic pollution and understand its environmental origins and impacts [12]. The movement and transport of MP in the aquatic environment and along food chains should also be taken into account, as this may provide insight into the potential effects of microplastic pollution on organisms at different trophic levels [13]. The major sources of environmental microplastics, their transport through atmospheric, terrestrial, and aquatic compartments, subsequent ecological consequences, and potential remediation pathways are collectively illustrated in Figure 2.

There are several path ways by which microplastics are altered in the environment, such as by the action of UV radiation, by microbial communities that degrade plastic polymers through enzymes, by chemical oxidation through reactive environmental species that modify polymer chains [1], [14], [15]. Microplastics can also bind, transport, enhance the bioavailability and enhance the impact in the presence of other pollutants [8].

In the context of chemical engineering, knowledge of the sources, transport, environmental fate and transformation of micro plastics is essential to create effective mitigation measures in the various environmental matrices [16].The occurrences of microplastics in the environment, analytical techniques for microplastic detection, the degradation and remediation of microplastics have been the topics of previous reviews, but these are considered individually. A comparative synthesis of selected studies addressing microplastic extraction, detection, degradation, and remediation is presented in Table 1, highlighting their methodological approaches, principal findings, limitations, and implications for future investigations.

2. Technological aspects of microplastics removal.

2.1. Current remediation technologies

2.1.1. Physical removal techniques

The common existing physical removal methods applied for wastewater treatment systems and aquatic systems, such as filtration and skimming, sediment dredging. The effectiveness of these methods, will vary based on the size of the microplastics and surrounding conditions [1]. Choosing the right solutions to marine plastic pollution should take into account effectiveness, environmental suitability, and challenges for implementation. Knowing what interventions are available will enable identification of suitable interventions to reduce the inputs of plastic pollution and to improve pollution management [17].

A comparative assessment of conventional and emerging microplastic remediation technologies is presented in Table 2, highlighting their underlying treatment mechanisms, potential advantages, operational limitations, and recommended performance metrics. Although physical separation methods are relatively established, advanced chemical, biological, photocatalytic, and nanotechnology-based approaches offer alternative pathways for microplastic removal or degradation. However, their practical applicability remains dependent on polymer characteristics, treatment efficiency, environmental conditions, operational costs, and the potential formation of secondary contaminants.

2.1.2. Chemical treatments

The AOPs can produce reactive oxygen species which can break down plastics, and coagulation-flocculation can be used to aggregate microplastics for removal. Such processes can be combined with Waste Water Treatment Plants (WWTPs) to improve the removal of microplastics [1].

2.1.3. Biological approach

Microorganisms like bacteria, fungi, algae which can break down plastic polymers. Enzymatic degradation is the process where specific enzymes are used to degrade polymer chains to harmless products. The use of genetically engineered microbial technologies and bioaugmentation could be options for improving these natural degradation processes [15]. The management of microplastic pollution necessitates a multi-faceted approach that encompasses pollution prevention, environmental monitoring, assessment, removal and mitigation technologies, as well as acknowledging the limitations and practicality of various microplastic treatment methods [18, 16].

2.2. Innovations and emerging techniques

Advancements in nanotechnology, involves photo responsive, magnetic-assisted cleaning microrobots which are able to remove micro plastics from water. These systems provide magnetic control and light-responsive functionality, which could be a viable option for microplastic removal under relatively low energy conditions [19].

Light-driven degradation of microplastics is an emerging technology, the processes activated by light contributes to the transformation of the polymer through photochemical reactions. Efficiency of the degradation is dependent on the polymer properties and experimental conditions. Other remediation methods involve using catalytic remediation materials like titanium dioxide, zinc oxide and decomposing microplastics into CO_2 and water or transforming them into useful products using photocatalytic degradation [14].

In recent times, the emergence of nanotechnology has led to the development of innovative magnetic nanorobots that can swiftly extract microplastics from water using agents that recognize them, removing them within minutes and in some instances with efficiencies exceeding 90%. The magnetic hybrid nanoparticles are capable of targeting specific microplastics while preventing secondary contamination and can be used multiple times [20].

Another possible way to remove the microplastics is through surface engineered materials. Research on the principles of designing capture and separation systems through the use of superhydrophobic materials and the intermolecular force interactions between the material surfaces and microplastic particles have been conducted. Such methods could offer ways to enhance the effectiveness and specificity of microplastic extraction, but their effectiveness must be tested in various environmental contexts [21]. The detection of microplastics and their removal by electrocoagulation are becoming more common because of their accuracy and effectiveness; however, further development is still needed [22].

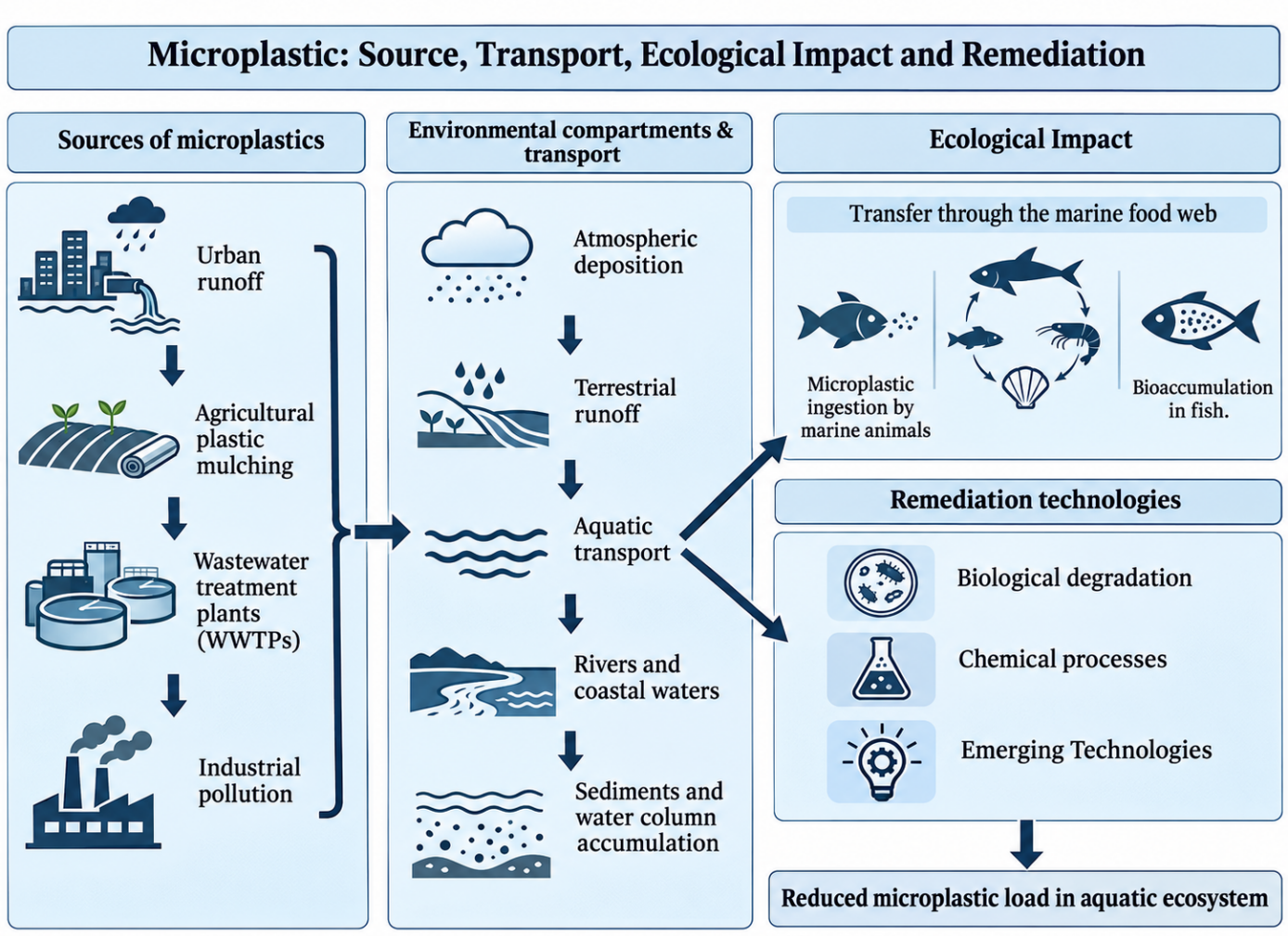


Figure 2: Overall understanding of environmental microplastics: sources, effects and mitigation.

2.3. Issues related to the introduction and use of technology.

It is also crucial to choose the suitable treatment options for the environmental matrix, the microplastic characteristics, and its purpose in preventing microplastic pollution. Therefore, a systematic assessment of management and mitigation options are needed to identify the technological constraints and prioritize the practical ones for the purpose of controlling pollution [18].

There are various challenges, such as the scalability of most of the advanced techniques, that are still in the experimental or pilot stage and optimization is required for economically viable applications on larger scales [7]. Different kinds and sizes of microplastics and different environmental matrices mean different pollution scenarios and hence flexible technologies for different types of pollution. There are various morphologies and polymer types and universal remediation is difficult [9]. The application of chemicals or nanomaterials can lead to unintended environmental pollution and risks, highlighting the importance of evaluating the potential for unintended ecological impacts during the cleanup process [20].

The adoption of interdisciplinary scientific innovations such as machine learning for microplastic detection and the development of novel materials, along with sustainable practices and regulatory frameworks, is crucial to tackle microplastic contamination, mitigate its potential long-term impacts on environmental and human health [1], [2], [23].

3. Socio-economic aspect of microplastic pollution

To direct allocation of resources, cost-benefit analyses of remediation technologies are needed. The use of new technology like Metal-Organic Frameworks (MOFs), membrane filtration and AOPs for the capture and degradation of micro plastics. Remediation pathways for microplastics by AOPs vary from around 30% to 95% catalytic degradation, and can be a more economically viable option than other methods like coagulation and biological treatment that involve further degradation steps. These methods need to be further validated in the field and toxicological testing of degradation products should be conducted [24], [25].

Toxicological and bibliometric investigations have been performed to assess the potential health effects of microplastic ingestion, and recent reviews have explored possible interactions with blood-tissue barriers as well as their health

Table 1: Comparative analysis of selected studies.

Study	Methods reported	Main findings	Limitation or implication	Ref.
Microplastic analysis and degradation studies	Harmonization and evaluation of analytical and experimental practices	Highlights persistent differences in study design and environmental conditions	Greater standardization and environmentally realistic testing are needed	[39]
Microplastics in agricultural soils	Comparison of oil extraction and density extraction	Demonstrates that extraction method selection should reflect soil-matrix characteristics	Extraction results may not be directly comparable across methods	[35]
Microplastic detection	Electrochemical sensing	Reviews sensor design, fabrication and applications	Further methodological development and validation are needed	[36]
Microplastics in *Mytilus galloprovincialis*	Machine-learning analysis of organism-associated pollution	Demonstrates the application of machine learning to microplastic analysis in marine organisms	Findings depend on data quality and validation	[38]
Microplastic removal from water	Photoresponsive, magnetic-assisted cleaning microrobots	Presents a light- and magnetically controlled capture approach	Performance requires evaluation under varied environmental conditions	[19]
Microplastic removal	Magnetic nanorobots and hybrid nanoparticles	Reports removal efficiencies exceeding 90% in some experimental settings	Field performance, reusability, cost and secondary effects require further assessment	[20]
Light-driven degradation	Photochemical and photocatalytic approaches	Describes light-driven transformation and degradation approaches	Outcomes depend on polymer properties and experimental conditions	[14]
Remediation and treatment economics	Review of Advanced oxidation processes (AOPs) and other treatment approaches	Reports catalytic degradation rates of approximately 30–95% for AOPs	Field validation and toxicity testing of degradation products are required	[24, 25]

impacts. The evidence available should be viewed with caution, however, and additional studies are needed to determine the scope and clinical relevance of these effects in humans [26], [27].

Trophozoite-accumulation and bioaccumulation of microplastics in the human body from eating seafood contaminated by micro-plastics and from toxic particles with harmful chemicals raises public health concerns. Experimental studies have also been verifying the harmful effects that microplastics can have on animals, plants and in drinking water, or the transfer of potentially toxic substances from plastic materials [28]. This can result in increased health care costs and reduced productivity. Economic costs are direct costs of remediation and indirect costs due to degradation of ecosystem services and impacts on health.

Another possible route of exposure in poultry products is the consumption of MPs resulting from environmental contamination, toxicity and potential human health effects have been studied [29]. Dental devices such as polymeric dental devices have also been a subject of discussions with regard to microplastics, such as orthodontic aligners and plastics in contemporary orthodontics [30].

Microplastic pollution is a problem in these industries, including fisheries, tourism and the health sector, among others, due to its economic impact. But not all exposure to microplastics in aquatic environments would directly lead to a reduction in fish stocks, it could suppress the growth of fish stocks and cause a negative impact on aquatic organisms, which could also lead to a reduction in fish stocks over time. This can decrease the livelihoods opportunities and economic vulnerability of fisheries dependent communities. Similarly, in the coastal and freshwater areas, the quality of water and scenic properties, and also affect the interest of the tourists [2].

To summarise, toxicological and bibliometric studies aimed at assessing potential health risk of microplastic exposure have been also investigated and emerging reviews have discussed the potential interactions with the blood-tissue barriers and the associated health effects. These effects have to be treated with caution, and further studies are needed to determine the extent and clinical significance of such effects in humans [26],[27]. Humans could be exposed to microplastics via food products and other environmental routes. As part of studies on microplastics in food, the detection methods with artificial intelligence, occurrence in foods and potential human health effects have been studied [31]. Besides the above, a review on plastic derived contaminants has considered the pathways through which these contaminants may be found in food and food chain and as human exposure [32].

Policy and regulatory interventions are an important tool in, microplastic pollution management toolbox. To minimize sources of microplastic pollution, there needs to be international agreements and national policies regarding plastic use and plastic waste. One such example is the European Union (EU) Microplastics Restriction Proposal (2023) which proposes to limit the release of microplastics. Novel technologies like biodegradable technologies and approaches for circular economy can be encouraged with funding and market-preferable remediation conditions, leading to their earlier adoption [1], [2].

Public participation and awareness can encourage policy action and behavioural change. Data collection and awareness of the data, as well as environmental protection, is supported by citizen science programmes and grassroots groups. Sensitisation on plastic waste and its consump-

Table 2: Comparative evaluation of conventional and emerging microplastic remediation technologies, including their mechanisms, potential advantages, limitations, and recommended performance metrics.

Technology	**Mechanism and intended outcome**	**Potential advantages**	**Limitations and risks**	**Recommended performance metrics**
Filtration [1], [18]	Size-based separation of microplastic particles from water.	Established treatment approach suitable for integration into wastewater treatment systems.	Efficiency depends on particle size, membrane properties, and water composition; generates contaminated residues.	Particle removal efficiency, filtration rate, energy consumption, and residual management.
Skimming [17]	Physical collection of floating plastic particles from water surfaces.	Simple operation and applicability to accessible surface contamination.	Limited effectiveness for submerged, dispersed, and smaller particles.	Collection efficiency, particle-size range, treatment area, and operating time.
Sediment dredging [18]	Physical removal of microplastic-contaminated sediments.	Potentially reduces accumulated contamination at selected sediment hotspots.	May disturb benthic habitats and resuspend contaminants; requires safe sediment disposal.	Sediment removal efficiency, residual particle concentration, ecological disturbance, and disposal requirements.
Coagulation–flocculation [1]	Aggregation of suspended microplastics into larger flocs for subsequent separation.	Compatible with conventional water and wastewater treatment processes.	Performance depends on polymer properties, coagulant dosage, and water chemistry; produces sludge.	Removal efficiency, chemical dosage, sludge generation, and residual microplastic concentration.
Advanced oxidation processes [24]	Generation of reactive species to promote polymer oxidation and degradation.	Potential for chemical transformation of microplastic particles.	Incomplete degradation, potentially toxic intermediates, and energy or reagent requirements.	Polymer degradation, mineralization efficiency, treatment duration, energy demand, and by-product toxicity.
Biological and enzymatic degradation [15], [42]	Microbial or enzyme-mediated breakdown of polymer chains.	Potential for selective polymer degradation under suitable biological conditions.	Polymer-dependent degradation rates, prolonged treatment periods, and incomplete mineralization.	Polymer mass loss, molecular-weight reduction, mineralization, treatment duration, and product toxicity.
Bioaugmentation and engineered microorganisms	Introduction or modification of microbial communities to enhance polymer degradation.	Potential improvement in biodegradation under controlled environmental conditions.	Variable environmental performance, microbial persistence, and possible ecological risks.	Degradation rate, mineralization, microbial stability, containment, and ecological effects.
Photocatalysis [14]	Light-activated catalysts generate reactive species that promote polymer degradation.	Potential for light-driven degradation using suitable catalytic materials.	Efficiency depends on irradiation, catalyst properties, polymer characteristics, and catalyst recovery.	Degradation efficiency, mineralization, light intensity, energy consumption, and catalyst reusability.
Electrocoagulation	Electrochemically generated coagulants promote microplastic aggregation and separation.	Electrically controlled treatment with potential integration into water-treatment systems.	Electrode consumption, energy requirements, sludge production, and variable treatment efficiency.	Removal efficiency, energy consumption, electrode loss, sludge generation, and residual particles.
Magnetic particles and microrobots [20]	Magnetically assisted capture, separation, and recovery of microplastic particles.	Rapid and potentially selective removal under controlled experimental conditions.	Limited field validation, material recovery challenges, operational costs, and secondary pollution risks.	Capture efficiency, treatment time, particle selectivity, recovery cycles, and residual nanomaterials.

tion can encourage behaviour changes. A fundamental way to develop inclusive, effective microplastic management policies is the collaborative effort of the Quintuple Helix which is composed of academia, government, industry, civil society, and environmental aspects [33], [34].

4. Development of new legal and policy solutions to micro-plastics

4.1. Sample preparation and extraction

When dealing with soil samples, the sample preparation and extraction should be taken into consideration for accurate quantification of microplastics. Comparative assessment of the extraction methods for agricultural soils (oil extraction, density extraction) showed the need to select a specific extraction method depending on the properties of the environmental matrix [35].

Over the years, analytical methods for detection and quantification of microplastics in environmental matrices have been improved. Detection methods have become a lot more sensitive and accurate, such as hyperspectral imaging, laser-induced breakdown spectroscopy (LIBS), Fourier-transform infrared (FTIR) and Raman spectroscopy, which are able to detect microplastics of about 100 nm. The issue of heterogeneity of environmental samples can be addressed by using ML methods able to detect MPs in very different environmental samples and to automatically identify MPs from complex data sets [1], [2].

Another new method for detecting the micro-plastics is electrochemical sensing. This research gives a thorough summary of the approaches that are used to design and fabricate sensors and their use in the latest research which also discusses the potential of sensors for microplastic analysis and the need for further methodological development and validation [36]. Besides particle identification, there have been recommendations to employ artificial intelligence (AI) tools to evaluate data quality for human health risk assessment of microplastics. They may be helpful in assessing reliability and consistency of evidence related to risk assessment [37].

In addition, machine learning has been studied as a tool to analyse the microplastic pollution in organisms such as the western Black Sea mussel Mytilus galloprovincialis as a base for the organism-based pollution analysis [38]. Sampling methods are not sufficiently standardized, however, to be able to compare studies. While there is progress in harmonizing microplastic analysis in ISO 24187:2023 there are still some differences in practice regarding the parameters used for microplastics such as particle size, material type, exposure time, environmental conditions etc. Such gaps hinder the understanding of data, building predictive models, and the development of policy programs [39].

Degradation rates and pathways are affected by environmental factors like pH, temperature, and microbial community composition. For example, the higher the temperature the faster the physicochemical degradation and microbial consortia acclimatised to their environmental conditions can impact the biodegradation process.

However, better simulation of aquatic and terrestrial conditions is required for degradation studies to better elucidate the results at the scale of the real-world situation [39], [40]. The development of new bioremediation approaches with potential to improve degradation of microplastics is being investigated. Possible health implications, degradation products, and conditions for successful treatment should be assessed for the effectiveness and environmental suitability [41].

The biotic and abiotic processes can break down the microplastics. Abiotic factors that can generate smaller particles include photolysis (UV), mechanical weathering and chemical oxidation. Biotic degradation is achieved by the action of microbial enzymes, such as PETase and laccase, generated by microorganisms such as Pseudomonas spp., Ideonella spp., and Aspergillus spp. Many factors, such as polymer types and environmental conditions, affect biodegradation efficiency [1], [42]. Figure 3 summarizes the integration of advanced analytical techniques and machine-learning-assisted identification with the principal abiotic and biotic degradation pathways of microplastics, including photolysis, mechanical weathering, microbial activity, and enzyme-mediated polymer breakdown.

5. Future directions and research gaps

Despite significant advances in understanding microplastic pollution, substantial research gaps remain regarding its long-term environmental fate, transformation mechanisms, ecological consequences, and effective remediation. Microplastics undergo complex physical, chemical, and biological transformations through photodegradation, mechanical weathering, chemical oxidation, and microbial or enzymatic activity. These processes are influenced by polymer composition, particle morphology, temperature, pH, ultraviolet radiation, and microbial community structure. Although microorganisms such as *Pseudomonas*, *Ideonella*, and *Aspergillus*, together with enzymes including PETase and laccase, have demonstrated potential for polymer degradation, their effectiveness under environmentally realistic conditions requires further investigation. Particular attention should be directed toward identifying intermediate transformation products, assessing their persistence and toxicity, and distinguishing polymer fragmentation from complete mineralization [39], [40], [42].

Standardization of analytical methods: Considerable differences in sampling procedures, extraction methods, particle-size thresholds, polymer identification, and reporting practices continue to limit comparisons across studies. Although advanced techniques such as Fourier-transform infrared spectroscopy, Raman spectroscopy, hyperspectral imaging, and laser-induced breakdown spectroscopy have improved microplastic characterization, their performance varies across environmental matrices. Machine-learning-assisted detection offers opportunities for automated identification and classification; however, reliable implementation requires representative datasets, standardized analytical procedures, and independent validation. Future investigations should prioritize harmonized protocols and consistent reporting of particle abundance, size distribution, morphology, polymer composition, and analytical uncertainty [23], [36], [39].

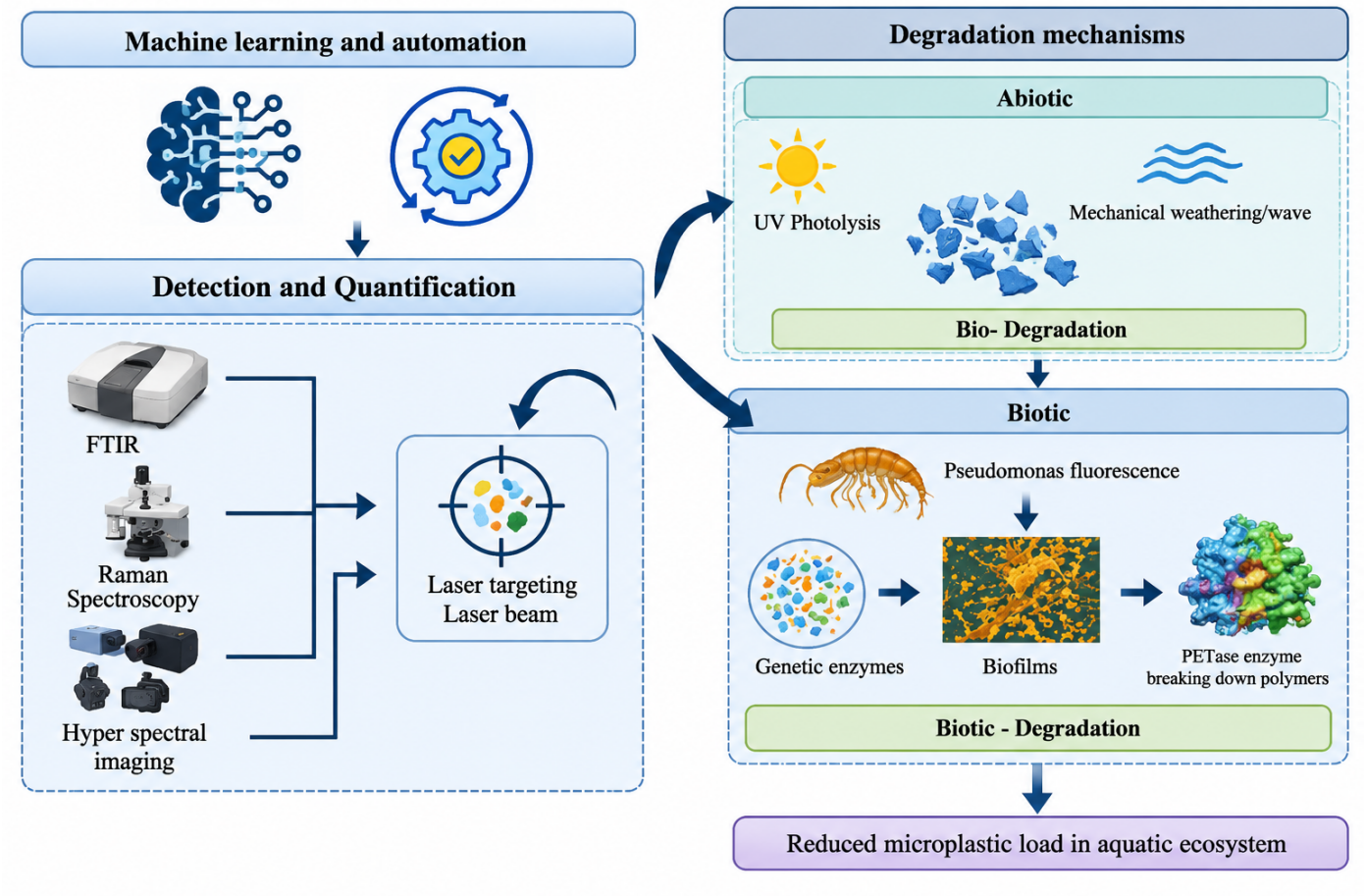


Figure 3: The detection, quantification and degradation mechanisms of microplastics in their Lifecyle.

Environmental fate and ecological risk: Further investigations are necessary to clarify the transport, accumulation, sedimentation, resuspension, and transformation of microplastics across aquatic, terrestrial, and atmospheric environments. Particular attention should be given to interactions with coexisting pollutants, including heavy metals, persistent organic pollutants, and microbial pathogens, which may influence contaminant transport and bioavailability. Long-term exposure studies are required to establish the relationships between microplastic characteristics, trophic transfer, bioaccumulation, ecosystem functioning, and potential human health consequences. Environmentally relevant exposure concentrations and realistic combinations of environmental stressors should be incorporated into future ecological risk assessments [2], [8], [13].

Remediation efficiency and technological scalability: Conventional physical separation methods, including filtration, skimming, and sediment dredging, remain important for microplastic removal but may transfer contamination into concentrated residual streams. Chemical treatments, such as coagulation–flocculation and advanced oxidation processes, and biological approaches involving microbial degradation, enzymatic treatment, and bioaugmentation provide alternative remediation pathways. Emerging technologies, including photocatalytic systems, electrochemical treatments, magnetic nanorobots, hybrid nanoparticles, and engineered capture materials, offer additional possibilities for selective removal and polymer transformation. However, their practical effectiveness depends on polymer characteristics, environmental conditions, treatment capacity, operational costs, and potential secondary pollution. Future studies should evaluate these technologies using realistic water, soil, and sediment matrices, with particular emphasis on pilot-scale demonstrations and field validation [14], [15], [18], [20], [24].

Treatment safety and performance evaluation: Reported microplastic removal efficiencies do not necessarily indicate complete degradation or environmental safety. Therefore, future research should distinguish physical particle capture from polymer degradation and mineralization. Standardized performance indicators should include particle removal efficiency, polymer-specific degradation, mineralization, treatment duration, energy and reagent consumption, operational cost, selectivity, material recovery, and reusability. Toxicological assessment of degradation intermediates, residual chemicals, catalysts, and nanomaterials is essential to prevent unintended ecological consequences. Comparative evaluations should also incorporate life-cycle considerations and the environmental burdens associated with treatment processes [18], [21], [24], [39].

Socioeconomic implications and policy integration: Microplastic pollution may impose direct and indirect economic burdens through environmental remediation, deterioration of ecosystem services, fisheries and tourism losses,

and potential public health concerns. Cost–benefit assessments are therefore necessary to prioritize remediation strategies according to technological feasibility, environmental benefits, and economic sustainability. Future management frameworks should integrate pollution prevention, circular economy principles, improved waste management, regulatory interventions, and incentives for sustainable materials and treatment technologies. Public awareness, citizen science, and cooperation among academic institutions, government agencies, industries, and civil society can support effective implementation. Multistakeholder governance approaches, including the Quintuple Helix framework, may facilitate the integration of scientific evidence, technological innovation, environmental protection, and policy development [2], [18], [33], [34].

6. Conclusion

This review synthesizes the sources, environmental distribution, fate, ecological consequences, detection methods, remediation technologies, and governance challenges associated with microplastic pollution. Primary and secondary microplastics enter aquatic, terrestrial, and atmospheric environments through direct emissions, plastic degradation, wastewater discharge, agricultural activities, surface runoff, and atmospheric transport. Their persistence, mobility, and ecological effects are governed by polymer characteristics, environmental conditions, degradation processes, and interactions with other contaminants. Microplastic exposure may affect aquatic and terrestrial organisms through ingestion, physiological disturbances, and trophic transfer, raising concerns regarding ecosystem stability and potential human health implications.

Advances in spectroscopic identification, hyperspectral imaging, electrochemical sensing, and machine-learning-assisted analysis have improved microplastic detection and characterization. Meanwhile, conventional physical separation, chemical treatment, and biological degradation remain important remediation approaches, complemented by emerging photocatalytic, electrochemical, and nanotechnology-based technologies. Nevertheless, treatment effectiveness varies considerably across polymer types and environmental matrices, while incomplete degradation, secondary contamination, operational costs, and limited field validation constrain practical implementation.

The review further identifies methodological inconsistencies, insufficient understanding of long-term transformation products, and limited evidence regarding ecological and human health risks as major research challenges. Addressing these limitations requires standardized analytical procedures, environmentally realistic experimental designs, comprehensive toxicity assessments, and comparable performance indicators. Effective microplastic management ultimately depends on integrating scientifically validated remediation technologies with pollution prevention, sustainable resource management, economic feasibility, regulatory frameworks, and public participation. Coordinated interdisciplinary research and evidence-based governance are therefore essential to reduce microplastic contamination and its potential long-term environmental consequences.

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CRediT authorship contribution statement

Nivin Kanth K: Data curation, Methodology & Writing-original draft. **Anjana Anoop P K**: Data curation & Writing-original draft. **Manoj K**: Supervision & Writing-review and editing

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