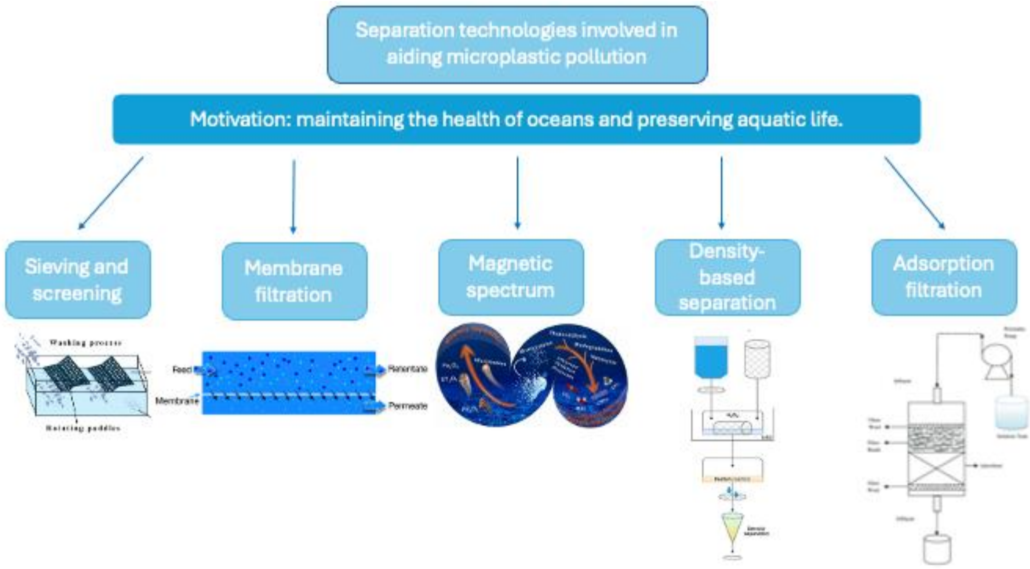
Separation Technologies and Policy Challenges in Addressing Microplastic Pollution

Olivia Mahony, Anne-Mari Callahan, Lily Wendler, Sabrina Salame and Minh Hao Le

The University of Sydney, Chemical and Biomolecular Engineering Department
E-mail: lwen0642@uni.sydney.edu.au

Graphical Abstract



Abstract

Microplastic accumulation in aquatic systems has emerged as a critical environmental and public health issue, with particles detected in human organs and across diverse ecosystems[1]. Despite growing awareness, current treatment technologies remain insufficient to address the pervasive contamination. Existing separation methods—physical, chemical, and biological—show variable efficiencies ranging from 65% to 100%, yet challenges persist due to microplastics' small size, heterogeneous composition, and continuous release into the environment[2]. Recent advancements include adsorption, membrane filtration, photocatalysis, electrochemical processes, and biological or enzymatic degradation, complemented by artificial intelligence-driven detection and hybrid systems integrating multiple mechanisms such as sieving, density, and magnetic separation[3]. However, literature highlights key challenges: limited scalability, energy intensity, secondary pollution, and inconsistent removal across particle sizes. To overcome these limitations, computational modelling and machine learning offer promising pathways for optimising process parameters, predicting separation efficiency, and designing adaptive treatment systems. Future research should focus on integrating advanced separation technologies into existing water treatment infrastructure, developing sustainable materials for microplastic capture, and establishing standardised assessment frameworks. Addressing these gaps is crucial to mitigate ecological disruption, protect biodiversity, and ensure safe water resources.

1. Introduction

1.1 Context and Relevance

Microplastics are small pieces of plastic less than 5 mm in size that can come from either primary sources - intentionally designed for use in industrial, commercial, or personal care products- or secondary sources - generated through the chemical, physical, and biological breakdown of larger plastic products[4]. These microplastics can enter the environment through spills or other releases during manufacturing or shipping, industrial process waste-stream management, and product use.

The growing global concern of the presence of microplastics is due to their persistent, low biodegradability and bio-accumulative behaviour. The pollution of microplastics has emerged as a critical environmental issue, with evidence of their presence across marine systems, terrestrial soils, and even atmospheric deposition. Studies have also reported the presence of microplastics in bottled water, tap water, table salt, seafood and even human blood and tissue, underscoring the pervasive nature of the problem and raising significant concerns over potential human health impact[5].

The worldwide production of plastic has increased dramatically, doubling from 2000 to 2019 and projected to increase further unless strong interventions are adopted. The OECD reports that plastic waste produced globally is on track to possibly triple by 2060 under these conditions[6]. The growth in plastic waste production has led to an increase in leakage of microplastics into the environment, with ramifications to ecosystems, human health, and economies.

In Australia, the Great Barrier Reef, an icon valued ecologically, economically and culturally, is under threat due to deteriorating water quality, with microplastic contamination being a growing component[7]. Microplastics threaten biodiversity, disrupt food webs, and may pose health risks, therefore, creating high environmental stakes. Therefore, it is imperative that the development separation processes are implemented as soon as possible.

From an economic and governance perspective, the required upgrades in infrastructure with advanced technologies, alongside regulatory and policy changes, represent very large investments. While the precise cost for these microplastic-specific treatments are still being established, preliminary studies reveal that some advanced wastewater treatments and separation processes are technically feasible and cost-effective, though trade-offs in energy, capital and operational expenses are non-trivial [7,8,9].

In summary, the global rise in plastic production and its leakage into natural systems highlight the urgent need for efficient microplastic separation strategies. This context establishes the environmental, economic, and policy rationale for evaluating treatment technologies in subsequent sections.

1.2 Background and literature review

Over the past decade, various separation methods including filtration, biological, and chemical, have been explored for removing microplastics from waste and wastewater. Membrane bioreactors, rapid sand filtration, coagulation/flocculation, adsorption, density separation, magnetic separation, and enzymatic or microbial degradation are among those studied. An example of one of these are membrane bioreactors combined with sludge treatment which have been identified as cost-effective options in certain contexts[7]. Reviews indicate that existing wastewater treatment plants can achieve high microplastic retention rates under specific conditions, yet many microplastics may still bypass treatment[8, 9, 10]. This highlights the inherent challenge of removing microplastics from the environment, due to their microscopic nature.

The bypassing of treatment shows how significant gaps in this technology still remain. Key challenges include energy, cost, and secondary pollution, as a higher removal efficiency often require a greater energy input, chemical usage, or generation of waste. Additionally, scalability is an ongoing obstacle to overcome, since full-scale implementation is still rare, even though it may perform well in lab or pilot settings. This is due to the heterogeneity nature of microplastics, which can complicate their separation and detection. Furthermore, policy and regulatory gaps due to the lack of standardized measurements, inconsistent regulation, and insufficient integration of separation technology into regulatory frameworks are a barrier to the elimination of microplastics.

In summary, while diverse physical, chemical, and biological separation methods have been tested, none yet deliver consistent large-scale removal across all microplastic types. These limitations underscore the importance of identifying performance gaps and innovation priorities, which are mapped in the next section.

1.3 Scope and Objectives

This review critically examines advanced separation technologies for microplastic removal, focusing on their performance, scalability, sustainability, and policy integration. It also assesses the legal, financial, and ethical challenges that influence deployment and global equity in access to clean water.

1.3.1: Objectives

- Synthesise findings from recent literature on the efficiency, mechanisms, and feasibility of physical, chemical, and biological microplastic-removal processes;

- Identify knowledge and performance gaps—including cost, energy use, and standardisation limitations—that hinder full-scale adoption;

- Evaluate the intersection between technological progress, policy frameworks, and economic realities to determine integration pathways; and

- Propose actionable directions for future research and investment, aligning engineering innovations with sustainability goals and regulatory development.

1.3.2: Scope and Roadmap

The included topics are: engineering separation technologies, process optimisation, scalability analysis, and policy implications. The excluded topics are: detailed toxicological mechanisms, nanoplastic (<1 µm) health effects, and polymer degradation chemistry beyond separation relevance. Collectively, this section establishes the conceptual framework for analysing microplastic sources and impacts, engineering separation processes, and the interconnected legal, financial, and ethical dimensions.

By outlining scope and objectives, this section provides a roadmap for how technological, policy, and economic lenses are integrated throughout the review to inform holistic solutions to microplastic pollution.

2. Origin and Accumulation of Microplastics

2.1 Sources

Microplastics are found everywhere in our everyday lives, infiltrating our water systems, ecosystems and even our blood systems. They can originate both from primary and secondary sources. Primary sources include those of intentionally manufactured microplastics, such as microbeads used in facial washes, nurdles, plastic-based glitters and more. Secondary sources include larger plastics which have deteriorated through means of mechanical abrasion, chemical hydrolysis, radiation and microbial digestion [11]. Common types of microplastics in the environment include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyamide (PA), and polyurethane (PU) [12].

Table 1: Common types and sources of microplastics [13].

Classification of microplastic	**Type of microplastic**	**Source of microplastic**
Primary microplastics	Microbead	Personal care and cosmetic items, such as exfoliating scrubs and toothpaste.
	Microfibre	Textiles like synthetic clothing, carpets, and home furnishings. Personal care products, including cigarette filters, wet wipes, and face masks.
	Resin particle	Plastic products
Secondary microplastics	Fragments	The breakdown of larger plastics.
	Fibre	Textiles, including garments, ropes, and fishing nets.

2.2: Accumulation and Harm of Microplastics

The accumulation of microplastics causes harm to all the ecosystems and environments they enter. Toxic pollutants such as polychlorinated biphenyls and dichlorodiphenyltrichloroethane (DDT) are absorbed by microplastics, thus can be transported more easily with plastic as their vector, while also persisting in the environment for much longer. Along with toxic pollutants, microplastics are also carriers for heavy metals, interacting with metals such as cadmium (Cd), lead (Pb), and arsenic (As)[14]. Heavy metals are detrimental to ecosystems as they are toxic to living organisms, posing major environmental and public health concerns, and in some cases are lethal to humans. Thus, the transport of such through microplastics is an additional complexity to the heavy metal pollution concern[15].

2.2.1: Human Body

Microplastics enter the human body through means of air, water and food, penetrating deep into the body and accumulating in tissue[16]. Microplastics have been detected in the blood, saliva, liver, kidneys, faeces, lung tissue, placenta and more[17]. Inhalation is a common route for microplastics into the human body; due of their size they evade the mucociliary clearance system and thus enter the upper respiratory tract, where they then circulate throughout the body via the upper digestive system and accumulate in various organs. Oral ingestion serves as another pathway into the human body. The intake of seafood is a major route for microplastics as they are commonly found within the tissues of marine organisms, thus facilitating their entry into humans. In Indonesia, it was discovered that 55% of fish samples were contaminated with microplastics. Bottled water similarly serves as a concern for microplastics ingestion, as consuming tap water leads to an estimated intake of 4000 microplastics annually, whereas bottled water can result in an additional intake of about 90,000 microplastics per year. Lastly, skin contact and dermal absorption similarly facilitate microplastics into the human body, for example, exposure to some cosmetics like body washes, topical medications or exposure to surgical or prosthetic devices[18].

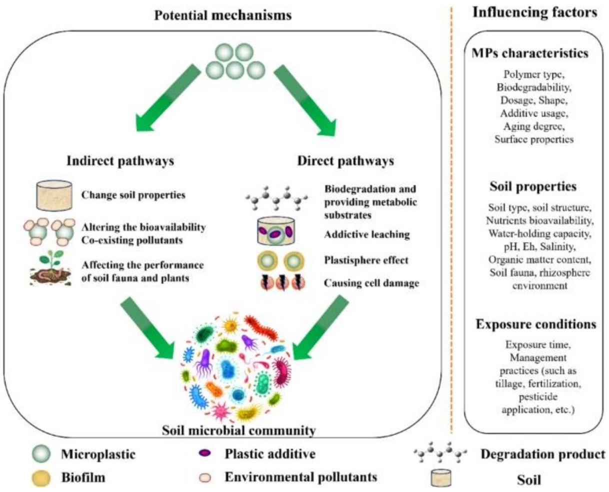
Due to microplastics' tendency to be a vector for toxic pollutants, these pollutants are released into an organism upon ingestion, resulting in toxicological effects like endocrine disruption, oxidative stress, abnormal growth patterns and many more. Cytotoxicity is an example of microplastics harm; they enter the cells and are enclosed by lysosomes for degradation, then are released into the cytoplasm. This can then result in mitochondrial dysfunction, which in turn increases the production of reactive oxygen species, an increase in such can undermine the cell's antioxidant defence systems, resulting in protein oxidation, lipid peroxidation and DNA damage. Neurotoxicity is another example, as smaller microplastics can cross the blood brain barrier and accumulate in the brain tissue, inflicting serious neuronal damage. Another implication on the brain are the reducing levels of synaptic proteins, which disrupt the neurotransmitter functions and induce neuroinflammation, which leads to deficits in learning and memory, as studied in mice. Other implications of microplastics' harm to the human body include oxidative stress, inflammatory reactions, apoptosis, gene damage, hepatoxicity, and respiratory toxicity[19, 20].

2.2.2: Soil Microbiomes

As other environmental systems, microplastics pose severe detriments to soil and the natural environment. For instance, in 2015, 79% of plastic waste ended up in landfills or the natural environment, ultimately invading soil and land. Plastics from landfills fragment and disperse into the environment through methods of leachate leakage, surface runoff, and wind dispersal, exacerbating environmental accumulation. Processes including flooding, atmospheric deposition, tire wear, and industrial/consumer waste disposal may also contribute to soil microplastic contamination. Microplastics accumulate rapidly and persist, remaining in the environment for at least 25 years, serving as a significant depository for microplastics with an annual input of plastic waste into terrestrial ecosystems exceeding that of oceans by 4 - 23 times. During their long life time they disrupt soil ecosystems by substantially altering soil structure, porosity, bulk density, water-holding capacity, pH value, and nutrient availability, therefore notably reducing soil health[21].

As previously discussed, microplastics have a tendency to carry heavy metals, and this leads to synergistic effects on plants, increasing the likelihood of plants becoming toxic, as both disrupt various biological and physiological processes. The presence of microplastics in soil will affect root development, soil aeration, diminishing soil fertility and altering the nutrient cycle[14].

Figure 2: Potential mechanisms of Microplastics on soil microbial communities



2.2.3: Marine Environments

Plastic and furthermore microplastics are a large contributor to marine pollution, they cover almost all aquatic environments and thus have reduced the sources for safe pollutant safe water, causing severe issues as the demand for water nearly doubles every 20 years, due to industrial expansion and population growth. It is estimated that 8 million tonnes of plastics enter the oceans and seas every year. Microplastics are among the most damaging and harmful marine pollutants. Plastics enter the ocean through urban, industrial, boating, shipping, fishing, and aquaculture activities, as well as accidents like container spills, shipwrecks, or collisions that release raw materials, which later degrade into microplastics[14].

Similar to humans, microplastics inflict harm on marine organisms, including genotoxicity, neurotoxicity, reduced feeding activity, growth delays, and decreased reproductive fitness[14]. As mentioned previously, microplastics have a tendency to attach to other harmful pollutants and in marine environments they attach to hydrophobic pollutants, which are not degradable and harmful to organisms[22]. Below in table 2 are examples of the harm microplastics cause to marine animals.

Table 2: Deleterious effects of microplastics on diverse types of marine animals[14].

Effects	Mechanisms	Marine animals affected

Physical ingestion: Blockage and damage of digestive systems, leading to starvation and reduced growth	MPs accumulate in the digestive tract, creating blockages or damaging internal tissues	- Zooplankton: Copepod (Neocalanus cristatus) - Crustacean: Norway lobster (Nephrops norvegicus) - Fish: salmon-bass (Argyrosomus regius) - Sea turtle: Loggerhead turtles (Caretta caretta)
Energy depletion: Reduced energy stores due to false satiation	Organisms sense “fullness” after ingesting indigestible MPs, leading to a lack of appetite	- Coral: Stony cup coral (Astroides calycularis) - Crustacean: Crab (Carcinus maenas) - Fish: Zebrafish (Danio rerio) - Sea turtle: Green turtles (Chelonia mydas)
Habitat disruption: Smothering of benthic habitats and coral reefs	MPs settle on seabed and reefs, physically blocking light and oxygen flow	- Coral: Branching coral (Pocillopora acuta), - Benthic invertebrates: Tubeworm (Spirobranchus triqueter)
Reproductive effects: Impaired reproduction, reduced fertility, and abnormal development	MPs interfere with gamete quality, embryo development, and larval growth	- Crustacean: Marine copepod (Tigriopus japonicus) - Mollusk: Pacific oyster (Crassostrea gigas) - Fish: Zebrafish (Danio rerio)
Immune suppression: Oxidative stress leading to reduced immune responses	Microplastic-induced stress lowers the ability to fight infections, increasing susceptibility to disease	- Crustacean: Pacific White Shrimp (Litopenaeus vannamei) - Mollusk: Blood clam (Tegillarca granosa)

3. Engineering Separation Processes for Microplastic Removal

3.1: Overview of Separation Methods

The separation of microplastics from water and wastewater has become a paramount focus of environmental engineering, and consequently, there are various processes for separation that are current, with more advanced processes emerging as the issue persists. These methods are grouped into four broad categories; mechanical size based separation, filtration technologies, density-driven processes and emerging advanced hybrid approaches[23]. Traditional physical methods like sieving, sand filtration and sedimentation are productive for larger particles, but are often unable to capture nano and micro-sized plastics, particularly in more complex environmental matrices. Conversely, more advanced methods, like membrane filtration, electrocoagulation and magnetic separation are effective in capturing smaller fractions, however, come at significantly higher costs combined with operational complexity, therefore are often unable to be used in less developed communities[23].

3.2: Sieving and Screening

Used as a pre-extraction technique, sieving and separation are moderately effective for the removal of larger microplastics (1.18–5 mm), still visible to the human eye[24]. This method separates microplastics from the soil, sand and sediment with the use of granulometric fractions, dividing it into different-sized components, allowing smaller particles to pass through, while retaining larger ones. It is a simple, low-cost separation method, with minimal energy demands[25]. For PET particles in the 1.18-5mm range, removal efficiencies reached up to 99.2%, while in a border range (0.15-5mm) the average was 76.1% [24]. This indicates that sieving is a highly effective technique when separating larger microplastics, however, as the particle size shrinks, it loses efficacy. As it is unable to remove a large amount of microplastics, sieving cannot be used as a separation method in isolation. This makes it useful as a pretreatment, removing larger coarse fragments before the use of one of the following separation methods.

3.3: Filtration Technologies

Similarly to sieving, filtration uses filters of specific pore size to separate a solid phase from a liquid phase, however on a more minute scale. It is often used in conjunction with other microplastic separation methods like density separation (5.4) and chemical digestion[26], either during stages, or at its beginning.

3.3.1: Membrane Filtration

Membrane filtration is a pressure-driven separation process, where water passes through a semi-permeable membrane while microplastics are retained. Membranes are specified by their pore size[27], with reduced sizes becoming increasingly more effective in retaining most microplastics; microfiltration (MF): 0.1-10 µm pores, ultrafiltration (UF): 0.01–0.1 µm pores, nanofiltration (NF): 0.001–0.01 µm pores and reverse Osmosis (RO) <0.001 µm pores, capable of retaining nearly all microplastics, and salts[28]. NF and RO membranes can remove over 95% of micro and nanoplastics in controlled conditions, however, as real-world applications introduce challenges, like fouling, membrane filtration becomes less effective. As separation in increasingly smaller pore sizes requires greater pressure[29],with RO requiring pressures between 30 and 80 bar[30], a trade-off between cost and efficiency emerges, requiring expansive amounts of energy to properly separate[31]. To combat this, a combination of membranes are used, where MFs and UFs are used first to filter out larger microplastics and reduce fouling, followed by NF and RO for finer microplastics and dissolved pollutants.

3.3.2: Adsorption Filtration

Adsorption filtration separates microplastics from water by binding them to porous mediums with large surface areas. Water passes through a column packed with adsorbent materials[32], with which the microplastics interact with and are subsequently retained. The treated water exits the stream with a reduced microplastic concentration. These adsorbents can be regenerated by washing, heating, or magnetic separation for reuse. Common adsorbents include activated carbon, clays, biochar, graphene-based materials and magnetically modified sorbents[33]. Depending on the absorbent utilised, this filtration is driven by different forces including Van der Waals forces, electrostatic interactions and hydrophobic interactions[34]. Activated carbon is the most industrially used adsorbent, capturing microplastics through hydrophobic interactions and capable of reaching removal rates of 90%. However, more typically ranging from 60-80%[35]. Despite not being used in full-scale treatment plants due to high variable dependence on the chemistry of the water (due to its low cost and versatile technique), it becomes a promising technique when combined with membrane filtration, to reduce fouling, operational costs, and energy consumption.

3.3.3: Magnetic Separation

An emerging separation method, used only at the lab scale at this stage, is magnetic separation. Essentially an extension of adsorption, it uses magnetically responsive materials like iron oxides to absorb and bind microplastics to their surface and then remove them using an external magnetic field. The magnetic particles can be either free nanoparticles which absorb microplastics through electrostatic interactions, hydrophobic interactions or functionalised composites, where the magnetic core is coated with sorbents like biochar or graphene oxide that aid microplastic adhesion. In recent lab tests, this strategy has at >95% removal consistently, with the use of Fe_3O_4-biochar composites[36].

3.4: Density-Based Separation

Density-based separation uses the density differences between plastics and the extraction solution to extract microplastics. These plastics will either float, if they are less dense than the medium (flotation), or sink, if they are denser (sedimentation). Using gravitational settling, sedimentation removes up to 50–70% of microplastics >300 μm, which are mostly fibres and fragments[37]. Moreover, air flotation units can recover 50-80% of lighter microplastics in lab scale studies. The separation process can be sped up, with the application of centrifugal forces accelerating the rate of sedimentation/flotation. By creating a hydrocyclone, sedimentation and flotation can occur at significantly faster rates, in a process that typically takes days to statically complete. Density-based separation works passively for large volumes of water, and requires low energy. However, it becomes ineffective when plastics have densities that are close to water, such as PET, PVC and PS, making separation unfeasible via sedimentation or flotation. In some large-scale separation plants, density-based separation is combined with NF and RO membrane filtration[38], creating a hybrid separation method that balances energy output and efficacy of microplastic removal

Table 3: Comparison Table of Microplastic Separation Technologies

Technology	Efficiency	Scale	Key Advantage	Limitations
Sieving and Screening	Up to 99.2% for large PETs (1.18–5 mm). Avg. 76% (0.15–5 mm)	Full-scale	Simple, low-cost, low-energy	Ineffective for particles <1 mm: only suitable as pretreatment
Membrane Filtration	>95% for NF/RO, MF & UF effective for larger MPs	Pilot to Full-Scale	Very high efficiency; capable of removing microplastics, nanoparticless, and salts	Fouling, high energy demand (up to 80 bar) and expensive operation
Adsorption Filtration	Typically 60–90%, depending on adsorbent and variables of medium	Lab to Pilot-Scale	Low-cost, regenerable, reduces membrane fouling	Variable efficiency, sensitive to water chemistry; not used standalone
Magnetic Separation	>95%, lab-scale using Fe_3O_4-biochar	Lab-scale (emerging)	Rapid, selective, reusable, low-energy	Nanoparticle leaching risk; currently unscalable

	composites			
Density-Based Separation	50–70% (sedimentation) 50–80% (flotation)	Lab to industrial-scale	Low-energy, scalable for large volumes, simple operation	Ineffective for plastics with densities similar to water (e.g. PET, PVC, PS)

4. Legal, Financial, and Ethical Considerations

4.1: Legal Considerations

To address general health hazards and different issues globally, the United Nations put in place their 16 Sustainable Development Goals. SDG 3,6,12,13 and 14 (Life Below Water) all indirectly address microplastic pollution, but only SDG 14 specifically targets plastics but excludes microplastics, and current monitoring still relies mainly on citizen science for larger debris, with no standardised international protocol yet in place[39]. Additional measures taken by the EU such as the Marine Strategy Framework Directive and the Water Framework Directive establish obligations for member states to monitor and reduce pollutants, but issues regarding microplastics and their regulations remain underrepresented[40]. Similarly, the U.S. Environmental Protection Agency has no specific regulations targeting microplastics, though the Microbead Free Waters Act of 2015 prohibited microbeads in cosmetics[41]. The OECD (Organisation for Economic Co-operation and Development) and non-OECD countries are adopting new measures to address plastic and microplastic pollution. They want to improve waste management policies, implement bans on frequently littered single use plastic items, and restrict the manufacturing and sale of personal care and cosmetic products containing microplastics. In addition, the OECD highlights that addressing microplastics from textiles and tyres requires policy mixes that combine innovation incentives, industry standards, and extended producer responsibility schemes to ensure long term reductions[42]. Despite these steps, the absence of harmonised global standards creates legal uncertainty for industries and utilities. If separation systems fail, liability may shift to municipal operators or technology providers, showing the urgent need for enforceable discharge limits in wastewater and drinking water systems.

4.2: Financial Considerations

In 2024, the global market for microplastic filtration systems was valued at USD 12.82 billion and is forecasted to reach USD 35.48 billion by 2034. Advanced separation processes such as membrane filtration, electrocoagulation, and hybrid technologies dominate the industry with their higher efficiencies but carry a high capital and have high operational costs, particularly due to membrane fouling, energy consumption, and maintenance requirements[43]. For developed economies, the costs can usually be managed by slowly upgrading their water systems. However, in developing countries, the high costs could make it harder for people to get equal access to clean water, creating inequalities in water access. Cost benefit analyses show that although microplastic removal technologies are expensive at the start, they can save money in the long run. A long-term economic benefit can be deduced through the reduction of health problems, lowering the costs of cleaning up damaged ecosystems, and protecting industries like fisheries, therefore the benefits outweigh the upfront investments. Regarding the adoption of a suitable solution will depend on the different socioeconomic context. No single solution works everywhere; the right choice depends on local conditions such as money, infrastructure, and community capacity[44].

4.3: Ethical Dimensions

The ethical considerations surrounding microplastic pollution are tied to various issues such as environmental and social justice, intergenerational equity, and corporate responsibility. Firstly, equitable access to clean water must be prioritised, imposing the cost of advanced treatment solely on communities with limited resources deepens global injustice. In addition, the long term and largely unknown health risks of microplastic exposure raises ethical and equity questions because vulnerable communities are likely to suffer the most from microplastic pollution, and waiting for complete proof before taking action can cause larger problems down the line. Therefore, there is abstraction of intergenerational justice,; future generations will have to deal with pollution and health issues they did not create and the long term persistence of microplastics shows that the damage accumulates over time. Furthermore, because microplastics are so small, people often overlook them and may not feel responsible for their impact, even though companies and individuals continue to pollute shared resources like oceans and air that everyone depends on, a problem known as the tragedy of the commons. From a global perspective, international justice is also impacted, since pollution crosses borders and all nations share responsibility for addressing it. Real solutions may require systemic change, with societies rethinking how plastics are produced, used, and valued. Ethical accountability lies not only with governments but also with plastic producing industries, which play a key role in both prevention and remediation of the issue[45]. Therefore, ignoring the health and ecological consequences of microplastics risks creating long lasting harm, raising serious questions about the responsibility of producers versus consumers in tackling plastic pollution.

5. Challenges and Future Perspectives

5.1: Identified Challenges

Although there are notable advancements within the field of separation processes for the removal of microplastics within our ecosystem, several persistent challenges limit real-world deployment. A major challenge is scalability: despite many processes performing well at lab-scale methods, it is unclear whether they would be feasible on a larger scale. This is because there are more factors that need to be taken into account, such as the economics of scaling up (for example the cost of equipment, staff, permits, etc). This is particularly applicable for developing nations, in which they would face energy and cost barriers, which would limit their applicability.

Maintenance is an important challenge to consider, due to material durability and reusability. In separation processes like membrane filtration and adsorption filtration, materials are a key component of the separation, therefore, the decision in selecting the material that is the most efficient, whilst also ensuring it is sustainable, durable, and if it can be reused. If it cannot be reused, then it must be considered as to how will it be disposed of in a sustainable manner.

Another identified challenge is the lack of standardised testing for removal efficiency. In 2023, the International Standardisation Organisation (ISO) published one of the first internationally recognised microplastic testing standards, ISO 24187 – Principles for the analysis of microplastics present in the environment. This document describes the principals to be followed in the analysis of microplastics in various environmental matrices[46] and provides guidelines for sampling, sample preparation, and data processing[47]. Although this is a step in the right direction, broad uptake and further method comparisons are required to enable reliable cross-study comparisons and regulatory acceptance.

5.2: Future Directions

As the worldwide consumption of plastic increase, it is imperative that we as a society implement the changes necessary to produce a difference, and to sustain the habitability of the earth for future generations. Looking forward, there are some key factors to apply, such as the need for standardised monitoring and reporting. The expansion of international standards is needed to harmonise reporting matrices, and regulation and monitorisation is essential in ensuring that the technologies developed are ethical and safe to use. This can be supported through policy-driven research funding and global cooperation. By investing into these emerging methods, it allows for the rapid development and scalability of the technologies, meaning it can be applied sooner outside of the laboratory.

Furthermore, despite the technologies being advanced, it is vital to ensure it is sustainable, low cost, and high efficiency, especially if they are to be used in less built-up areas. Additionally, its maintenance must be considered, as this can provide unnecessary barriers. This ensures that there is a bridge between lab-scale operations and worldwide implementation.

By combining clear regulations and technological innovation, this will improve that the feasibility of microplastic separation solutions, and help translate promising lab results into quantitative reductions of microplastics in our environment.

6. Conclusion

This review has reaffirmed the significance of the removing microplastics from our oceans and ecosystems. They are at the centre of various environmental concerns, such as the release of toxic additives[48] and its bioaccumulation in marine life. Therefore, its remediation is critical.

The main method of achieving so is through separation processes – this is central to the solution; however, it is not sufficient to remove the copious amounts from our oceans. A combined engineering and policy approach is needed to ensure that the application of the separation processes discussed is implanted in an efficient manner.

Sophisticated separation techniques must be complimented by robust policy, increased international standards, and investments into scale-ups to produce notable change, to create a greater environment for all and preserving the natural beauty of our planet.

References

[1] Mohammadi, A., Hashemi, B., Mohseni, M., & Hazrati, S. Microplastics in environment: global concern, challenges, and controlling measures. *Int. J. Environ. Sci. Technol.* 19, 4809–4830 (2022).

[2] Dayal, L., Yadav, K., Dey, U., Das, K., Kumari, P., Raj, D. & Mandal, R. Recent advancement in microplastic removal process from wastewater: a critical review. *J. Hazard. Mater. Adv.* 16, 100460 (2024).

[3] Raja Namasivayam, S. K. & Avinash, G. P. Review of green technologies for the removal of microplastics from diverse environmental sources. *Environ. Qual. Manage.* (2023).

[4] Interstate Technology and Regulatory Council (ITRC). Types of Microplastics: Primary & Secondary (ITRC, 2024).

[5] Leonard, S. V. L., Liddle, C. R., Atherall, C. A., Chapman, E., Watkins, M., Calaminus, S. D. J. & Rotchell, J. M. Microplastics in human blood: Polymer types, concentrations and characterisation using μFTIR. Environ. Int. 188, 108751 (2024).

[6] Organisation for Economic Co-operation and Development (OECD). Policy scenarios for eliminating plastic pollution by 2040 (OECD, 2024).

[7] CSIRO. *Impacts on the Great Barrier Reef.* CSIRO (2024). Available at: https://www.csiro.au/en/research/environmental-impacts/sustainability/Managing-impacts-GBR

[8] Ahmed, S. F. *et al.* Microplastic removal and management strategies for wastewater treatment plants. *Chemosphere* **347**, 140648 (2024).

[9] Liu, W. *et al.* A review of the removal of microplastics in global wastewater treatment plants: Characteristics and mechanisms. *Environment International* **146**, 106277 (2021).

[10] Lu, Y., Li, M.-C., Lee, J., Liu, C. & Mei, C. Microplastic remediation technologies in water and wastewater treatment processes: Current status and future perspectives. *Science of The Total Environment* **868**, 161618 (2023).

[11] Rani, A. Types and Sources of Microplastics; The Ubiquitous Environment Contaminant: A Review. *Journal of Polymer Materials* **39**, 17–35 (2022).

[12] Wang, K. *et al.* Microplastics and soil microbiomes. *BMC Biology* **23**, 273–273 (2025).

[13] Zhang, X., Yu, C., Wang, P. & Yang, C. Microplastics and human health: unraveling the toxicological pathways and implications for public health. *Frontiers in Public Health* **13**, (2025).

[14] Ahmad, O. *et al.* Microplastic pollution in the marine environment: Sources, impacts, and degradation. *Journal of Advanced Veterinary and Animal Research* **12**, 260 (2025).

[15] Mitra, S. *et al.* Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University - Science* **34**, 101865–101865 (2022).

[16] Hong, Y., Gan, S. K.-E. & Shim, B. S. Microplastics in human body: accumulation, natural clearance, and biomedical detoxification strategies. *Biomedical Engineering Letters* (2025) doi: https://doi.org/10.1007/s13534-025-00511-6

[17 Dutchen, S. Microplastics Everywhere. *Harvard.edu* https://magazine.hms.harvard.edu/articles/microplastics-everywhere (2023).

[18] Zhang, X., Yu, C., Wang, P. & Yang, C. Microplastics and human health: unraveling the toxicological pathways and implications for public health. *Frontiers in Public Health* **13**, (2025).

[19] Lee, Y., Cho, J., Sohn, J. & Kim, C. Health Effects of Microplastic Exposures: Current Issues and Perspectives in South Korea. *Yonsei Medical Journal* **64**, 301–301 (2023).

[20] Li, Y. *et al.* Microplastics in the human body: A comprehensive review of exposure, distribution, migration mechanisms, and toxicity. *Science of The Total Environment* **946**, 174215 (2024).

[21] Aralappanavar, V. K. *et al.* Effects of microplastics on soil microorganisms and microbial functions in nutrients and carbon cycling – A review. *Science of The Total Environment* **924**, 171435 (2024).

[22] Guin, M. & Singh, N. B. Removal of hydrophobic pollutants from water using adsorption and degradation method with special reference to biosurfactants. *Elsevier eBooks* 227–273 (2021) doi:https://doi.org/10.1016/b978-0-12-822696-4.00009-7.

[23] Rani, M. et al. A Complete Guide to Extraction Methods of Microplastics from Complex Environmental Matrices. Molecules 28, 5710–5710 (2023).

[24] Staplevan, M. J., Ansari, A. J., Ahmed, A. & Hai, F. I. Effect of embedding a sieving phase into the current plastic recycling process to capture microplastics. Journal of Water Process Engineering 66, 106075–106075 (2024).

[25] Zhang, S. et al. A Low-Cost Approach for Batch Separation, Identification and Quantification of Microplastics in Agriculture Soil. Toxics 11, 461–461 (2023).

[26] Lusher, A. L., Munno, K., Ludovic Hermabessiere & Carr, S. Isolation and Extraction of Microplastics from Environmental Samples: An Evaluation of Practical Approaches and Recommendations for Further Harmonization. Applied Spectroscopy 74, 1049–1065 (2020).

[27] Saboya, L. & J.-L. Maubois. Current developments of microfiltration technology, in the dairy industry. Dairy Science & Technology 80, 541–553 (2000)

[28] Cherian, A. G., Liu, Z., McKie, M. J., Husein Almuhtaram & Andrews, R. C. Microplastic Removal from Drinking Water Using Point-of-Use Devices. Polymers 15, 1331–1331 (2023)

[29] Zahra Pazhouhnia, Nima Beheshtizadeh & Nasrin Lotfibakhshaiesh. Encapsulation of cartilage cells. Elsevier eBooks 525–555 (2023) doi:https://doi.org/10.1016/b978-0-12-824345-9.00022-2.

[30] Charcosset, C., Falconet, C. & Combe, M. Hydrostatic pressure plants for desalination via reverse osmosis. Renewable Energy 34, 2878–2882 (2009).

[31] Gude, V. G. Energy consumption and recovery in reverse osmosis. Desalination and Water Treatment 36, 239–260 (2011).

[32] Mentari Noviyanti Puteri, Gew, L. T., Ong, H. C. & Ming, L. C. Technologies to eliminate microplastic from water: Current approaches and future prospects. Environment International 109397–109397 (2025) doi:https://doi.org/10.1016/j.envint.2025.109397.

[33] Solcova, O., Dlaskova, M. & Kastanek, F. Innovative Sorbents for the Removal of Micropollutants from Water. Molecules 30, 1444 (2025).

[34] Barberi, J. & Spriano, S. Titanium and Protein Adsorption: An Overview of Mechanisms and Effects of Surface Features. Materials 14, 1590–1590 (2021).

[35] Laca, A. et al. PERFORMANCE OF ACTIVATED CARBON FOR POLYPROPYLENE MICROPLASTIC REMOVAL IN WASTEWATER. Sustainable Chemistry for the Environment 100211–100211 (2025) doi:https://doi.org/10.1016/j.scenv.2025.100211.

[36] Cao, Y. et al. Advances in magnetic materials for microplastic separation and degradation. Journal of Hazardous Materials 461, 132537–132537 (2023).

[37] Cavazzoli, S. et al. Effectiveness of conventional municipal wastewater treatment plants in microplastics removal: Insights from multiple analytical techniques. Journal of Environmental Sciences (2025) doi:https://doi.org/10.1016/j.jes.2025.04.035.

[38] Zhang, Y., Bu, X., Dong, X., Wang, Y. & Chen, Z. Nanofiltration combined with membrane capacitive deionization for efficient classification and recovery salts from simulated coal chemical industrial wastewater. Separation and Purification Technology 322, 124156–124156 (2023).

[39]. Enfrin, M., Dumée, L. F., & Lee, J. (2019).

[40] European Union. (2008). *Marine Strategy Framework Directive (2008/56/EC)*. EUR-Lex. https://eur-lex.europa.eu/EN/legal-content/summary/strategy-for-the-marine-environment.html

[41] Wikipedia contributors. (2023, December 5). *Microbead-Free Waters Act of 2015*. In *Wikipedia*.

[42] OECD. (2021). *Policies to reduce microplastics pollution in water: Focus on textiles and tyres (Policy Highlights)*. Organisation for Economic Co-operation and Development. https://www.oecd.org/content/dam/oecd/en/publications/support-materials/2021/10/policies-to-reduce-microplastics-pollution-in-water_3337bc78/policy-highlights-policies-to-reduce-microplastics-pollution-in-water-focus-textiles-and-tyres.pdf

[43] Polaris Market Research. (2024). *Microplastic filtration systems market share, size, trends, industry analysis report, 2024–2034*. Polaris Market Research. https://www.polarismarketresearch.com/industry-analysis/microplastic-filtration-systems-market#:~:text=In%202024%2C%20the%20membrane%20filtration%20systems%20segment,technology%20to%20remove%20microplastics%20from%20water%20sources

[44] Nikiema, J., & Asiedu, Z. (2022). A review of the cost and effectiveness of solutions to address plastic pollution. *Environmental Science and Pollution Research*, 29, 65645–65667. https://pmc.ncbi.nlm.nih.gov/articles/PMC8783770/

[45] Sustainability Directory. (2023). *What are the ethical considerations surrounding microplastic pollution and its impact on future generations?* Sustainability Directory. https://sustainability-directory.com/question/what-are-the-ethical-considerations-surrounding-microplastic-pollution-and-its-impact-on-future-generations/

[46] *Principles for the analysis of microplastics present in the environment Principes d'analyse des microplastiques présents dans l'environnement*. https://cdn.standards.iteh.ai/samples/78033/ab8efdddef164bc0b1aff6b25bfb9669/ISO-24187-2023.pdf.

[47] Rajala, A. New microplastic testing standard ISO 24187 sets guidelines for analysis. *Measurlabs.com* https://measurlabs.com/blog/microplastic-testing-standard-iso-24187/ (2024).

[48] Ibukun Oluwoye, Tanaka, S. & Okuda, K. Pilot-scale performance of gravity-driven ultra-high flux fabric membrane systems for removing small-sized microplastics in wastewater treatment plant effluents. *Journal of Environmental Management* **363**, 121438–121438 (2024).