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MICROPLASTICS IN AQUATIC ECOSYSTEMS: PATHWAYS, IMPACTS AND INTEGRATED SOLUTIONS FOR ENVIRONMENT AND HUMAN HEALTH

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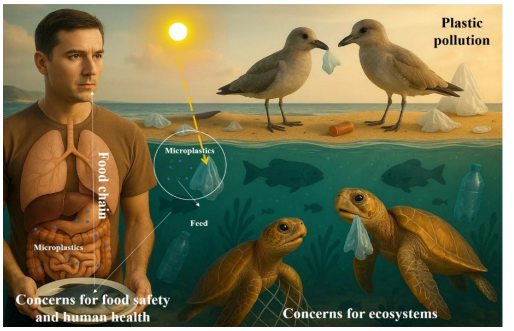
HIGHLIGHTS

- Microplastics are widespread in freshwater and marine environments.
- Wastewater, runoff, and plastic degradation are key pathways of microplastic entry.
- Microplastics accumulate in aquatic organisms and move through food webs.
- Human exposure to microplastics raises concerns about chronic health effects.
- Integrated upstream and downstream strategies are critical for pollution control.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic pollution has rapidly evolved into a global environmental crisis, with microplastics emerging as ubiquitous and persistent contaminants across freshwater and marine ecosystems. This review synthesises current knowledge on the origin, distribution, and ecological consequences of microplastics, emphasising their complex environmental behaviour and widespread biological uptake. Microplastics are introduced through diverse pathways, including wastewater effluents, urban and agricultural runoff, atmospheric deposition, and the degradation of larger plastic debris. Once in the aquatic environment, they undergo transformation via photochemical, mechanical, and biological processes, facilitating their dispersal and interaction with biota and co-pollutants. The ingestion of microplastics by a wide range of organisms has been documented, with evidence of bioaccumulation, trophic transfer, and physiological harm. Moreover, microplastics act as vectors for hazardous chemicals and pathogens, raising critical concerns for food safety and human health. Current removal technologies are limited

in scope and efficiency, particularly in natural settings. This review highlights the pressing need for coordinated multidisciplinary approaches that address both prevention and remediation. A bold, global response that integrates upstream interventions (e.g., reduced plastic use and improved product design) with downstream innovations (e.g., advanced filtration, bioremediation, and robust policy enforcement) is essential to mitigate the long-term impacts of microplastic pollution and safeguard aquatic ecosystems and public health.

Introduction

Plastic production has undergone exponential growth since the mid-20th century, evolving into one of the most pervasive and rapidly expanding industrial sectors globally (Zalasiewicz *et al*., 2016). Annual output has risen dramatically from just 1.5 million tonnes in 1950 (Okeke *et al*., 2022) to 367 million metric tonnes by 2020, representing a 220-fold increase (Xia *et al*., 2024). This surge has been primarily driven by escalating demand across diverse sectors, including packaging, automotive, electronics, healthcare, and construction. The overwhelming majority of plastics are derived from fossil hydrocarbons, specifically coal, oil, and natural gas (Singh *et al*., 2022), through highly energy-intensive polymerisation and polycondensation processes (Edmondson and Gilbert, 2017). These processes contribute substantially to greenhouse gas emissions, exacerbating climate change by intensifying the global carbon burden (Kiehbadroudinezhad *et al*., 2023). Currently, approximately 4% of extracted fossil fuels are used as feedstock for plastic production, predominantly from natural gas liquids and low-value gaseous fractions generated during petroleum refining. However, projections indicate that by 2050, plastic manufacturing may consume up to 20% of the world's petroleum supply and account for as much as 15% of the global carbon emissions budget (Lebreton & Andrady, 2019).

The environmental impact of plastics extends far beyond their production phase; in fact, the consumption and post-consumption stages may pose even greater ecological threats. Discarded plastic products, including bags, bottles, and packaging, will ultimately accumulate in landfills, rivers, and marine ecosystems. Currently, it is estimated that 22% to 43% of plastic waste ends up in landfills, and this figure is expected to increase (Rajmohan *et al*., 2019). This is primarily due to the non-biodegradable nature of plastics, which often contain toxic additives and can persist in the environment for up to 1,000 years (Zhang *et al*., 2021). Indeed, plastic waste, due to its slow degradation and tendency to release harmful substances, should be viewed as a serious environmental risk (He *et al*., 2024).

Plastics constitute a significant portion, approximately 50% to 60%, of municipal solid waste in many regions, encompassing a broad range of polymers (Donuma *et al*., 2024). Their proliferation not only mars the landscape and waterways but also poses severe threats to wildlife. A 2015 review reported a notable rise in seabird entanglement, with affected species increasing from 16% to 25% in just over two decades (Ryan, 2018). The impact of plastic waste exposure to birds ranges from acute effects, such as asphyxiation and gastrointestinal blockage, to sub-lethal outcomes like impaired

growth, internal trauma, inflammation and uptake of endocrine-disrupting chemicals (Schutten *et al*., 2024).

The escalating accumulation of plastic waste on land inevitably extends its environmental footprint to aquatic ecosystems (Nam *et al*., 2022). Plastics enter these systems through multiple pathways, including littering, stormwater runoff (Brooks *et al*., 2023), industrial effluents (Thathapudi *et al*., 2024), and poorly regulated waste disposal (Thushari and Senevirathna, 2020). Once introduced, plastics will end up disrupting aquatic habitats by entangling organisms and causing sub-lethal and lethal effects through ingestion (Welden, 2020). A significant proportion of plastic pollution reaching the oceans, estimated to be between 2.8% and 18.6% of coastal plastic emissions, originates from rivers, with Asian waterways accounting for 86% of this total global input. This pattern is closely linked to high population densities, widespread waste mismanagement, and intensified discharge during seasonal floods (Chowdhury *et al*., 2021). The accumulation of plastics in rivers and streams will block water flow and increase the risk of flooding, which has direct consequences for human communities (Pattnaik *et al*., 2025). In marine ecosystems, plastic debris accumulates along coastlines and in open oceans (Kalčíková and Gotvajn, 2019), posing significant risks to a diverse range of organisms, including deep-sea fish, marine mammals, turtles, and birds (Lambert *et al*., 2020).

Beyond the visible menace of macroplastic debris, a far more insidious threat lurks in aquatic environments: The generation and spread of microplastics. Once plastic waste enters freshwater and marine systems, it undergoes progressive degradation into tiny fragments through a complex interplay of degradation processes (Li *et al*., 2020). Environmental weathering, including sunlight, wind, wave action, mechanical abrasion from water currents, and human activities, such as fishing and boating, accelerates this fragmentation. Ultraviolet radiation, oxidation, and hydrolysis further weaken the polymer bonds in plastics, while microbial colonisation and the activity of aquatic organisms contribute to their physical breakdown (Banaee *et al*., 2024).

These particles, typically smaller than 5 mm (Koelmans *et al*., 2022), now permeate virtually every aquatic niche, from surface waters and shorelines to deep-sea sediments. Alarmingly, microplastics have been detected in some of Earth's most remote and extreme environments, including the summit of Mount Everest, the Mariana Trench, and Antarctic ice shelves. Their global proliferation, particularly in marine ecosystems, has escalated into a critical environmental concern (Bai *et al*., 2023). Estimates suggest that nearly 270,000 tonnes of microplastics and plastic debris are floating on the ocean's surface alone (Cormier *et al*., 2021), and once dispersed, these microscopic fragments are virtually unrecoverable (Isobe, 2016). Due to their small size, microplastics are readily ingested by a vast range of organisms, raising serious concerns about bioaccumulation, trophic transfer, and long-term ecological harm (Guzzetti *et al*., 2018).

Table 1 provides a global snapshot of microplastics detected across diverse aquatic environments, reinforcing their ubiquitous presence in both freshwater and marine systems (Gola *et al*., 2021). The findings reveal that the polymers comprised polystyrene, polypropylene, polyethylene, nylon, polyester, and polyvinyl chloride, all of which are widely used in consumer and industrial products. Microplastics have been reportedly found in geographically and ecologically distinct regions, including China's Three Gorges reservoir, the Southern Caspian Sea, the Andaman and Nicobar Islands, and the coastal zones of Indonesia and Pakistan.

Their varied morphologies, including fibres, fragments, pellets, foams, films, and filaments, point to multiple sources and complex degradation processes. The consistent detection

of microplastics across such disparate regions underscores the global scale and persistence of this pollution threat, emphasising the pressing need for coordinated monitoring, source control, and mitigation strategies.

Table 1: Microplastics found in various water bodies (Gola *et al*., 2021). Used with permission from Elsevier. Copyright©2022, Licence Number: 6034770841216

Type of Microplastic	Sample and Place	Shape	References
Polystyrene, polypropylene, and polyethylene	Surface water and sediments from the Three Gorges reservoir, China	Fibres, pellets, fragments, etc.	(Di & Wang, 2018)
Polystyrene, polypropylene, and polyethylene	Surface water and sediments from the Southern Caspian Sea	Foam and fragments	(Mataji *et al*., 2020)
Nylon, polystyrene, and polyethylene	Surface water and sediments from the Andaman and Nicobar Islands	Fibres, fragments, and foam	(Goswami *et al*., 2020)
Polystyrene, polypropylene, polyvinyl chloride, polyethylene, etc.	Surface water and sediments from the southwest coast of Kerala	Fragment fibres and foam	(Robin *et al*., 2020)
Polystyrene, polypropylene, polyvinyl chloride, polyethylene, etc.	Surface water and sediments from Rawal Lake, Pakistan	Fibres and fragments	(Irfan *et al*., 2020)
Polypropylene	Sediments and seawater at the Tambak Lorok coastal area, Indonesia	Fibres and filaments	(Khoironi *et al*., 2020)
Polyester and nylon	Surface water and sediments from the Ciwalengke River, Indonesia	Fibres	(Alam *et al*., 2019)
Polyvinylchloride, polyamide, polyethylene, and polypropylene	Water from Nansha Islands in the South China Sea	Fibres, pellets, fragments, and films	(Nie *et al*., 2019)
Polyester, polypropylene, and polyethylene	Water from Maowei Sea, China	Fibres, foam, and fragments	(Zhu *et al*., 2019)

Microplastics can enter the human body through various pathways, including ingestion of contaminated food and water (Al Mamun *et al*., 2023), inhalation of airborne particles (Chen *et al*., 2025), and possibly dermal contact (Hofstede *et al*., 2023). Once absorbed, they may translocate to critical organs such as the lungs (Dong *et al*., 2023), liver (Horvatits *et al*., 2022), kidneys (La Porta *et al*., 2023), and skin (Aristizabal *et al*., 2024), where they accumulate and exert toxic effects. As illustrated in Figure 1, exposure to microplastics has been associated with oxidative stress, inflammation, tissue irritation, and even DNA damage, all mechanisms that could potentially contribute to the development of chronic diseases, including cancer (Sangkham *et al*., 2022). Additionally, microplastics may generate reactive oxygen species (ROS) (Das, 2023), interfere with cellular functions, and circulate throughout the body via the bloodstream (Sangkham *et al*., 2022). These findings underscore the urgent need for comprehensive regulatory frameworks and intensified research efforts to understand and mitigate the health implications of microplastic exposure fully.

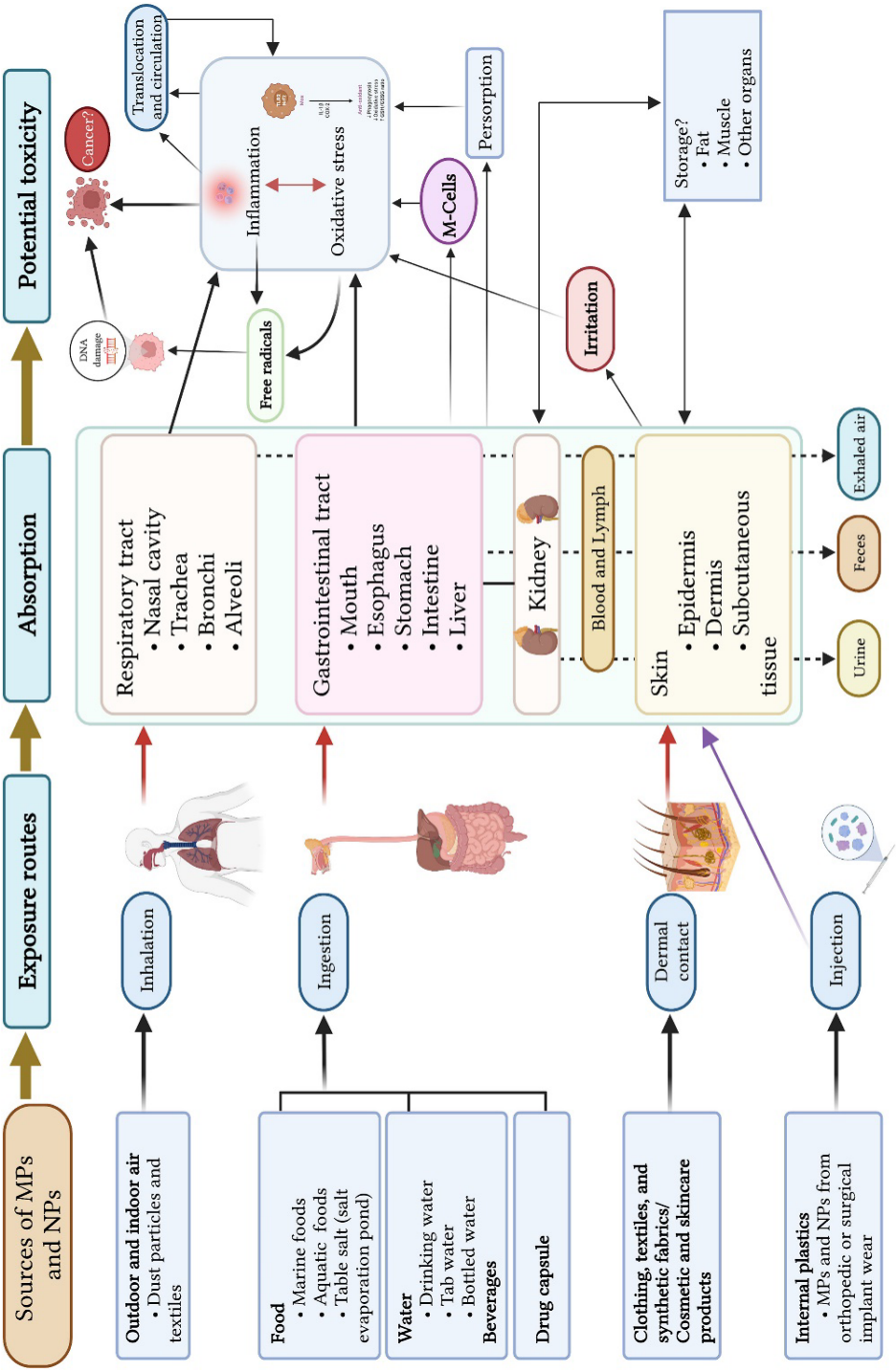

Figure 1. Potential pathways of micro- and nanoplastic exposure and their toxic impact on human health. Used with permission from Elsevier. Copyright©2022, Licence Number: 6034770475853

Source: Sangkham *et al.* (2022)

Figure 1 indicates that microplastics and nanoplastics can enter the body through inhalation, ingestion, dermal contact, or injection. Once absorbed through the respiratory tract, gastrointestinal tract, skin, or bloodstream, they may accumulate in organs and also excreted through urine, faeces or exhalation. Given that water sources are a significant pathway for microplastics to enter the human body, this study aims to investigate the distribution and characteristics of plastic pollution across both marine and freshwater systems. Understanding the prevalence and behaviour of plastics in these environments is critical, as they serve as primary channels through which microplastics are introduced into ecological food webs and, ultimately, into human populations. Despite increasing awareness about the hazards, substantial gaps remain in identifying the specific sources, types, and transport mechanisms of plastic contaminants in aquatic systems.

Addressing these gaps is crucial for informing targeted mitigation strategies, guiding regulatory policies, and ensuring the safeguarding of ecosystem integrity and public health. Therefore, this study aims to assess plastic pollution patterns in diverse water bodies comprehensively. While numerous reviews have examined the presence and impacts of plastics in aquatic environments, most focus either on marine or freshwater systems in isolation or emphasize broad ecological effects without integrating human health perspectives. This review offers a comprehensive synthesis that bridges both marine and freshwater contexts, highlighting the transport pathways, degradation mechanisms, and ecological as well as toxicological consequences of microplastics. By combining environmental distribution patterns with an analysis of human exposure risks, this work provides a holistic perspective that addresses critical knowledge gaps and supports the development of targeted mitigation and regulatory strategies.

Section 2 examines the pathways, sources, and environmental behaviours of microplastics in freshwater environments. Section 3 shifts focus to marine ecosystems, discussing the distribution, ecological impacts, and transport dynamics of microplastics. Section 3 also evaluates current mitigation strategies, including physical, chemical, and biological removal techniques.

Microplastics in Freshwater Ecosystems

Microplastics originate from diverse sources and are introduced into freshwater systems through several pathways. Key routes of contamination include effluents from wastewater treatment plants, urban surface runoff, industrial discharges, agricultural runoff/soil, leachate from landfills, atmospheric deposition, recreational activities, and fragmentation of larger plastic debris.

Wastewater treatment plants (WWTPs) represent a critical pathway for microplastic contamination in freshwater environments. Domestic wastewater, like laundry discharge and sewage, contains substantial quantities of microplastics from synthetic textiles, personal care products, and cleaning agents (Patil *et al*., 2024). Despite their primary role in pollution mitigation, WWTPs are not fully effective in eliminating microplastics. Influent concentrations have been reported to range from 1.01 to 31,400 particles per litre, whereas treated effluents can still contain 0.004 to 447 particles per litre, reflecting a highly variable removal efficiency spanning from 10.2% to 99.9% (Cheng *et al*., 2021; Estahbanati and Fahrenfeld, 2016).

Even advanced treatment technologies often fail to entirely prevent microplastics from entering waterways. Furthermore, the application of sewage sludge, rich in retained microplastics, as fertiliser in agricultural systems introduces a secondary emission pathway, thereby extending microplastic pollution from aquatic to terrestrial

ecosystems (Zhang *et al*., 2020). Consequently, WWTPs have become inadvertent conduits for the dissemination of microplastics across environmental compartments (Kalčíková *et al*., 2017).

Urban environments are also emerging as significant sources of microplastic contamination, primarily through stormwater runoff exacerbated by rainfall (Cho *et al*., 2023). Urban landscapes encompass a range of diffuse microplastic sources, including atmospheric deposition, vehicular emissions, construction materials, and human activities (Kim and Lee, 2024). Among these, road surfaces, particularly those subject to heavy traffic, have been identified as the dominant contributors to urban microplastic pollution (Kim & Lee, 2024). Road dust, a key carrier of microplastics, originates from the wear and tear of rubber tyres, thermoplastic road markings, polymer-modified bitumen, and other roadside plastic fragments (Monira *et al*., 2021). During precipitation, stormwater mobilises these particles and transports them into drainage networks, which frequently discharge untreated runoff directly into adjacent freshwater systems (Jefferson *et al*., 2017). This process is intensified by the prevalence of impervious surfaces in urban areas, which limit infiltration and amplify the volume and velocity of contaminated runoff. Critically, stormwater bypass systems have been shown to contain elevated concentrations of microplastics, particularly in the uppermost water layers, underscoring the inefficacy of current urban runoff management systems in mitigating microplastic discharge (Österlund *et al*., 2023).

Moreover, industrial activities represent major point sources of microplastic pollution. Facilities involved in the production of plastics, synthetic textiles, packaging, and personal care products frequently release primary microplastics, including pellets, synthetic fibres, and resin fragments, through inadequately treated wastewater (An *et al*., 2020). Accidental spills, operational losses, and poor waste handling further exacerbate microplastic emissions, particularly in proximity to industrial zones (Gomiero *et al*., 2018). These contributions highlight the need to accelerate the development of urban and industrial mitigation frameworks to address the growing burden on freshwater environments.

Agricultural activities are also increasingly recognised as significant sources of microplastic contamination (Li *et al*., 2023). A primary pathway is the application of sewage sludge (biosolids) on farmland (Mohajerani and Karabatak, 2020). Additionally, the degradation of plastic mulch films, greenhouse covers, and polymer-based irrigation components under field conditions generates microplastic fragments that accumulate in agricultural soils (Qi *et al*., 2020). These particles can be mobilised by rainfall, surface runoff, and irrigation drainage, ultimately entering nearby rivers, lakes, and streams (Wang *et al*., 2022). Other sources include polymer-coated fertilisers (Lian *et al*., 2021) and wastewater-based irrigation (Aydin *et al*., 2025), both of which contribute to the long-term accumulation of microplastics in soil. During heavy precipitation or irrigation events, these particles are transported via runoff, facilitating the transfer of persistent plastic pollutants from terrestrial to aquatic environments.

Landfills serve as long-term reservoirs of plastic waste, gradually releasing microplastics into the environment through multiple pathways (Wojnowska-Baryła *et al*., 2022). Rainwater infiltration generates leachate, a complex, contaminated liquid often containing microplastic particles. This leachate can contaminate groundwater or discharge into adjacent surface waters. For example, 17 plastic polymers have been identified in landfill leachate (0.42 to 24.58 items/L), predominantly polyethylene and polypropylene, with 99.36%

of microplastics originating from fragmented waste and 77.48% measuring between 100 µm and 1,000 µm (He *et al*., 2019), underscoring the long-term release potential of buried plastics. In addition to leachate, wind-driven dispersal of plastic debris from landfill surfaces also contributes to the contamination of nearby terrestrial and aquatic ecosystems (Kannankai & Devipriya, 2024).

Recreational activities in freshwater systems, such as boating, fishing, bathing, and washing, will introduce microplastics from ropes, equipment, and boat coatings (Talukdar *et al*., 2023). In addition, airborne microplastics from urban dust, synthetic fibres, and emissions from industrial processes can be deposited into freshwater bodies via precipitation or dry fallout, particularly affecting remote or less urbanised areas. Finally, larger plastic debris discarded or transported into freshwater environments will undergo progressive degradation. Over time, exposure to ultraviolet radiation, mechanical abrasion, and microbial activity leads to the fragmentation of these materials into secondary microplastics. Figure 2 illustrates the diverse pathways through which microplastics enter freshwater systems.

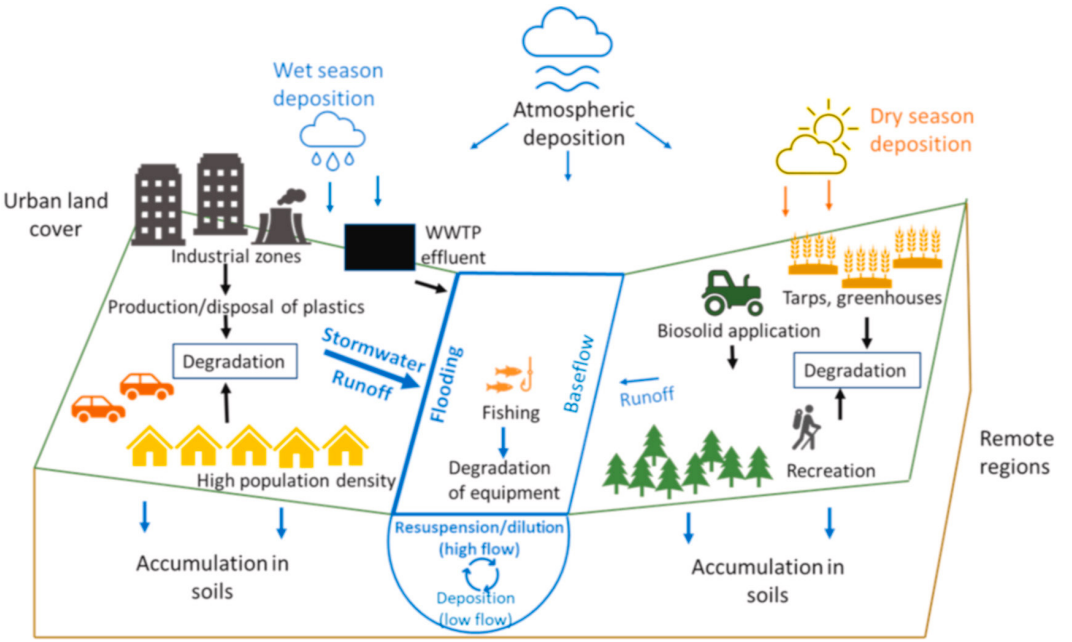

Figure 2: Key spatial and temporal drivers shaping freshwater microplastic abundance and distribution
Source: Talbot and Chang (2022)

Figure 2 illustrates the sources of microplastic pollution, including industrial zones, wastewater treatment plants, and agricultural land. It describes how pollutants are transported through atmospheric deposition, stormwater runoff, and baseflow, with accumulation in soils and aquatic systems. Processes such as degradation, resuspension, and deposition influence the persistence of microplastics across different land uses and seasons.

These diverse pathways highlight the complex and multifactorial nature of microplastic pollution in freshwater systems. Table 2 further substantiates this by presenting empirical evidence of microplastic contamination across a wide range of global freshwater environments, capturing the spatial variability, particle characteristics, and analytical approaches employed in current research. Based on Table 2, the studies span multiple continents, including locations in Asia (e.g., China, India, Malaysia), Europe (e.g., UK, Italy, France), North and South America (e.g., USA, Canada, Brazil), Africa (e.g., Tunisia, South Africa), and Oceania (e.g., Australia). Microplastic concentrations in sediments and surface waters vary widely, ranging from as low as 0.00297 g/L (3.3 particles/L) in treated effluent water in the Netherlands (van Wezel *et al*., 2016) to 2.5803 g/L (2867 particles/L) in Australia's Maribyrnong and Yarra Rivers (Kowalczyk *et al*., 2017).

The sizes of microplastics also exhibit substantial variability, ranging from a few micrometers (e.g., 3 µm to 178 µm in Malaysia; Praveena *et al*., 2018) to 5 mm, with some classifications extending beyond this range. Techniques used in size determination include visual inspection, energy-dispersive X-ray spectroscopy (SEM-EDS), Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, and digital microscopy, reflecting a wide methodological spectrum. While some of the highest concentrations were reported in urban or industrial areas, such as the lagoon of Bizerte in Tunisia (2.106 g/L; Toumi *et al*., 2019) and Lake Winnipeg in Canada (1.7397 g/L Anderson *et al*., 2017), even remote sites like lakes in the Tibetan Plateau (0.5067 g/L; Zhang *et al*., 2016) and Easter Island (0.072 g/L; Hidalgo-Ruz and Thiel, 2013) showed significant microplastic contamination. The findings show that microplastic contamination is not confined to oceans, but is a widespread issue, reflecting its diffuse and multifaceted origins.

Table 2: Concentrations and sizes of microplastics found in freshwater environments (Li *et al*., 2020).
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Country	Location	Average Concentration from the studies	Estimated MP units/ L	Sample	Size	Methods	Reference
UK	Kelvin River	0.26685 g/L	296.5	Sediment	Size classes: 2.8 mm-11 μ m	SEM-EDS	(Blair *et al*., 2019)
China	Poyang Lake	0.2034 g/L	226	Sediment and Surface Water	Size classes:< 0.5 mm	Raman	(Yuan *et al*., 2019)
Europe	Carpathian basin	0.4716 g/L	524	Sediment and surface water	Size classes: < 0.3 mm	FTIR	(Bordós *et al*., 2019)
Tunisia	The lagoon of Bizerte	2.106 g/L	2340	Sediment	Size classes: 5 – 0.2 mm	FTIR	(Toumi *et al*., 2019)
China	Wei river	0.918 g/L	1020	Sediment and surface water	Size classes: < 5 mm	Microscope with digital camera	(Ding *et al*., 2019)
Belgium	Flemish rivers	0.0153 g/L	17	Water	Size classes: < 5 mm	FTIR and Raman	(Slootmaekers *et al*., 2019)
Australia	Bloukrans River	0.216 g/L	240	Sediment	Size classes: 500 μm	Visual Inspection	(Nel *et al*., 2018)
Malaysia	Surface water in Malaysia	0.108 g/L	120	Surface water	Size classes: 3 −178 μm	Visual Inspection	(Praveena *et al*., 2018)
Australia	Maribyrnong and Yarra Rivers	2.5803 g/L	2867	Surface water	Size classes: < 2 mm	Visual Inspection	(Kowalczyk *et al*., 2017)
Canada	Lake Winnipeg	1.7397 g/L	1933	Surface water	Size classes: < 5 mm	SEM-EDS	(Anderson *et al*., 2017)
India	Vembanad Lake	0.27 g/L	300	Sediment	Size classes: 0.2−1 mm	Raman	(Sruthy and Ramasamy, 2017)

Netherlands	Dutch wastewater treatment plant effluent	0.00297 g/L	3.3	Wastewater treatment plant effluent water	Size classes: < 5 mm	Visual Inspection	(van Wezel *et al.*, 2016)
Canada	Canadian lakes and rivers	0.495 g/L	550	Sediment and surface water	Size classes: 2 - 5 mm	Visual Inspection	(Anderson *et al.*, 2016)
China	Remote lakes in the Tibet Plateau	0.5067 g/L	563	Sediment	Size classes: < 5 mm	Raman	(Zhang *et al.*, 2016)
Italy	Lake Chiusi and Lake Bolsena	2.5 particles/m^3	0.025	Sediment and surface water	Size classes: < 5 mm microplastics	Visual inspection	(Fischer *et al.*, 2016)
China	Taihu Lake	123 particles/L	123	Sediment and surface water	Microplastics with a size of 100–1000 μm	FTIR and SEM/ EDS	(Su *et al.*, 2016)
Brazil	Jurujuba Cove, Niterói, RJ	0.099 g/L	110	Sediment and surface water	Size classes: < 5 mm	FTIR	(Castro *et al.*, 2016)
South Africa	Five urban estuaries of KwaZulu-Natal	0.288 g/L	320	Sediment and surface water	Size classes: < 5 mm	Visual Inspection	(Naidoo *et al.*, 2015)
France	River Seine, urban area	3 particles/m^3	0.03	River water	100–5000 μm	Visual inspection	(Dris *et al.*, 2015)
China	Pearl River Estuary	0.468 g/L	520	Sediment and river water	Size classes: 0.315 – 5 mm	Visual Inspection	(Fok and Cheung, 2015)
Mongolia	Lake Hovsgol	1.2×10^4 particles/ km^3	0.00012	Lake water	Size classes: 0.355–0.999 mm, 1.00–4.749 mm, and > 4.75 mm	Visual inspection	(Free *et al.*, 2014)
Chile	Easter Island	0.072 g/L	80	Sediment and surface water	Quadrat: 0.25 m^2; Depth: 2 cm; Sieve: 1 mm	Visual Inspection	(Hidalgo-Ruz and Thiel, 2013)

South Korea	Heungnam beach	0.3285 g/L	365	Sediment and surface water	Quadrat: 0.25 m^2; Depth: 5 cm; Sieve: 2 mm	Visual Inspection	(Heo *et al*., 2013)
Denmark	Danish waters	0.0324 g/L	36	Sediment	Size classes: 38 µm – 1 mm, 1–5 mm and > 5 mm	FTIR	(Strand *et al*., 2013)
Italy	Lake Garda	1.7×10^3 particles/m^3	17	Sediment	Size classes: 9–500 µm, 500 µm–1 mm, 1–5 mm, > 5 mm	Raman	(Imhof *et al*., 2013)
USA	Great Lakes	1.6×10^7 particles/km^3	0.016	Surface water	Size classes: 0.355–0.999 mm, 1.00–4.749 mm, > 4.75 mm	SEM/EDS	(Eriksen *et al*., 2013)
Switzerland	Various lakes	2×10^3 particles/m^3	20	Sediment and surface water	Size classes: < 2 mm, < 5 mm (sediments) < 5 mm, > 5 mm (water)	Visual inspection	(Faure *et al*., 2012)
USA and Canada	Lake Huron	3.5×10^{11} particles/km^3	3499	Sediment	Size classes: < 5 mm plastic pellets, > 5 mm broken plastic, polystyrene	FTIR	(Zbyszewski and Corcoran, 2011)

Various physical, chemical and biological processes shape the fate of microplastics in freshwater systems (Atugoda *et al*., 2022). Hydrodynamic conditions, such as flow velocity, turbulence and stratification, play a crucial role in determining their transport and distribution. While high-density microplastics typically settle into sediments through gravitational processes, even low-density particles like polyethylene can accumulate in sediments due to interactions with biological and chemical components (Xia *et al*., 2021). The formation of biofilms and aggregation with organic matter or minerals can significantly alter their buoyancy, promoting deposition or resuspension (Li *et al*., 2023). These transformations not only prolong the persistence of microplastics in aquatic environments, but also increase their capacity to adsorb and transport hazardous contaminants, including heavy metals and pathogens, thereby amplifying their ecological threat (Tang *et al*., 2021). Despite growing concern, integrated field-based studies that capture the full complexity of these processes remain limited, leaving critical gaps in our understanding of their long-term fate and environmental consequences.

Microplastics in Marine Ecosystems

Marine plastic pollution poses a profound and escalating threat to environmental integrity, biodiversity and global socio-economic stability. It affects a wide range of sectors, including tourism and fisheries, as well as international shipping, and presents growing risks to food security and public health. The transboundary nature of marine plastic pollution necessitates robust international collaboration and policy coherence (Tessnow-von Wysocki and Le Billon, 2019).

The scale of this crisis continues to intensify. According to the United Nations International Resource Panel, plastic leakage into the ocean is projected to nearly triple by 2040 if current trends persist (Bertolazzi *et al*., 2024). Alarmingly, an estimated 10% of global plastic waste enters the oceans annually, with predictions suggesting that by 2050, plastic debris could outweigh the biomass of fish (Schmaltz *et al*., 2020). Already, more than 150 million tonnes of plastic have accumulated in marine environments, a burden compounded by inadequate waste management infrastructures and insufficient recycling capabilities (Tessnow-von Wysocki and Le Billon, 2019).

Table 3 presents an overview of the primary classes of plastics commonly found in marine environments, detailing their specific gravities, production proportions and typical sources (Andrady, 2011). Polymers such as low-density polyethylene (LDPE/LLDPE) and polypropylene (PP) are most prevalent, accounting for 21% and 24% of global plastic production, respectively. Their low specific gravities (0.91 to 0.93 for LDPE and 0.85 to 0.83 for PP) enable them to remain buoyant, making them especially abundant on the ocean surface. These plastics are typically derived from disposable consumer products such as plastic bags, bottle caps, six-pack rings and netting. High-density polyethylene (HDPE), with a specific gravity of approximately 0.94 and a 17% production share, is also frequently found in surface waters, primarily from milk and juice containers.

In contrast, denser polymers such as polyethylene terephthalate (PET, 1.37), polyvinyl chloride (PVC, 1.38), and polystyrene (PS, 1.05) are more likely to sink and become embedded in sediments, depending on environmental conditions. These are commonly used in beverage bottles, food packaging and plastic films. Despite its altered density characteristics, foam polystyrene, often used for floats and bait boxes, also contributes to marine debris. Nylon (PA), predominantly found in fishing gear such as nets and traps, and cellulose acetate (CA), primarily derived from cigarette filters, represent smaller fractions of plastic

production, but are still significant contributors to marine pollution. This diversity in polymer types, densities and usage patterns contributes to the varied distribution, transport behaviour and environmental impact of plastics in aquatic ecosystems.

Table 3: Classes of plastics commonly encountered in marine environment (Andrady, 2011). Used with permission from Elsevier. Copyright©2022, License Number: 6034780665852

Plastic Class	Empty Cell	Specific Gravity	Percentage production	Products and typical origin
Low-density polyethylene	LDPE LLDPE	0.91-0.93	21%	Plastic bags, six-pack rings, bottles, netting, drinking straws
High-density polyethylene	HDPE	0.94	17%	Milk and juice containers
Polypropylene	PP	0.85-0.83	24%	Rope, bottle caps, netting
Polystyrene	PS	1.05	6%	Plastic utensils, food containers
Polystyrene foam				Floats, bait boxes, foam cups
Nylon	PA		< 3%	Netting and traps
Thermoplastic polyester	PET	1.37	7%	Plastic beverage bottles
Poly(vinyl chloride)	PVC	1.38	19%	Plastic film, bottles, cups
Cellulose acetate	CA			Cigarette filters

Unlike large plastic debris, microplastics in marine environments are nearly impossible to detect, collect or remove. Their small size and widespread dispersion make conventional clean-up ineffective, particularly in coastal waters where floating microplastic concentrations can reach 10^3 to 10^4 particles per cubic metre (Andrady, 2017). Microplastics have been detected in a wide range of marine organisms, including fish, sea turtles and seabirds, with mounting evidence suggesting their potential for bioaccumulation and transfer through the food web (Kurniawan *et al*., 2021). This poses a threat to marine biodiversity and raises urgent questions about the implications for human health and food safety, underscoring the need for comprehensive monitoring and prevention strategies.

Indeed, a critical concern is the ingestion of microplastics by commercially important seafood species. Sharp or irregularly shaped particles can cause physical damage, such as intestinal blockage or internal injury (Ahrendt *et al*., 2020), which reduces feeding efficiency and leads to starvation and death (Bucci *et al*., 2020; Catarino *et al*., 2021). Abandoned fishing gear, a significant source of plastic debris, further exacerbates these threats by continuing to trap marine organisms long after it is disposed of (Walkinshaw *et al*., 2020). Moreover, microplastics act as vectors for a variety of chemical contaminants. Their hydrophobic surfaces readily adsorb persistent organic pollutants, heavy metals and pathogens, potentially transferring them into the food web upon ingestion. Studies in fish have linked microplastic exposure to a range of metabolic and physiological disorders (Figure 3), underscoring the urgency for coordinated global monitoring, risk assessment and pollution prevention strategies to safeguard marine ecosystems and food safety.

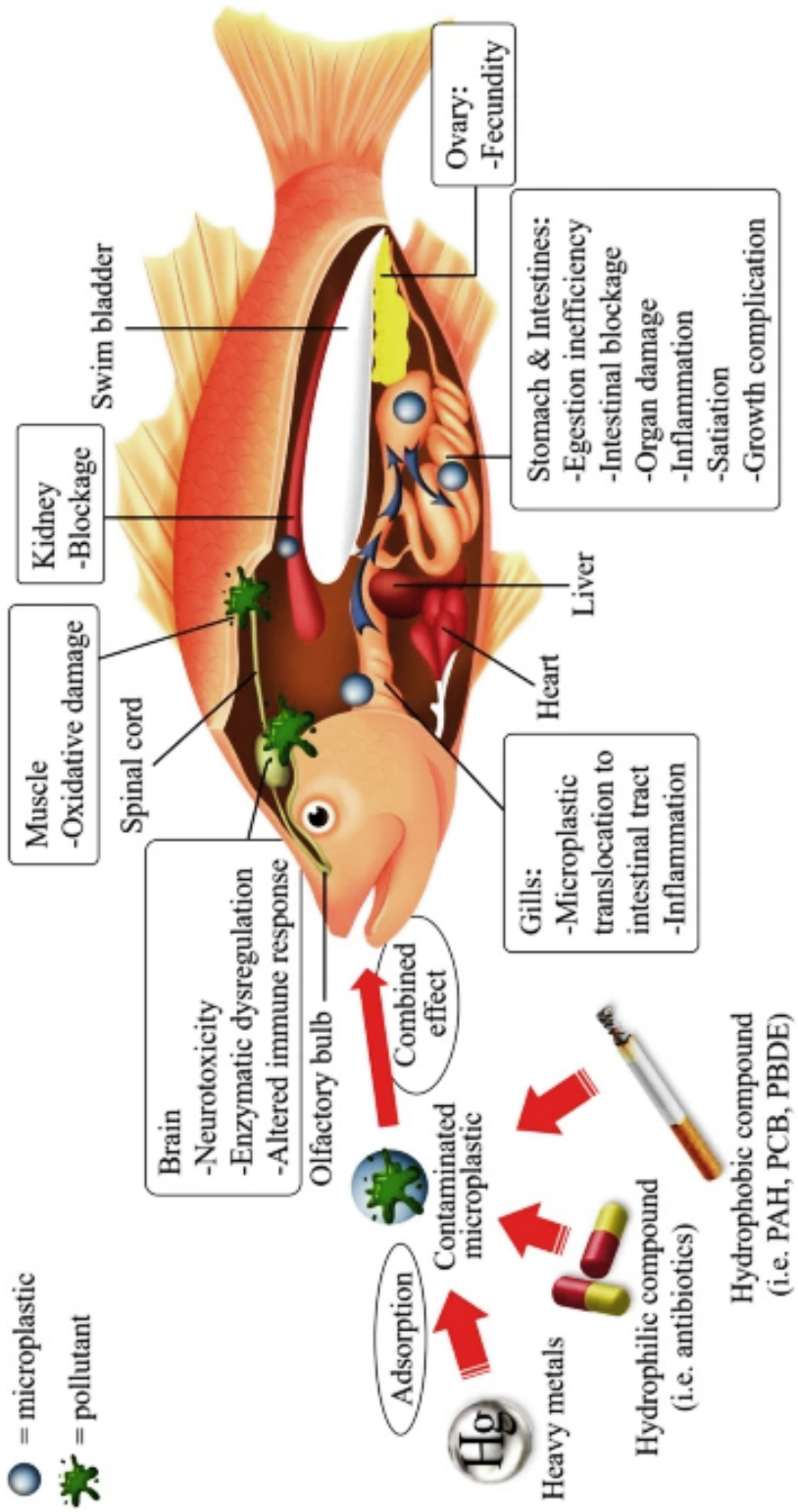

Figure 3: Schematic representation of the impacts and synergistic effects of microplastics and associated pollutants on marine organisms (Amelia *et al.*, 2021)

Figure 3 shows the effects of contaminated microplastics (combined with pollutants like heavy metals, antibiotics, and hydrophobic compounds) on fish physiology. Adsorbed pollutants enter the fish via ingestion or respiration, leading to neurotoxicity, oxidative damage, inflammation, organ dysfunction, and reproductive issues across multiple organs, including the brain, gills, stomach, intestines, kidneys, and ovaries.

The presence of microplastics in the marine food web raises significant concerns for human health, particularly through the consumption of contaminated seafood. Humans are primarily exposed to microplastics through three main routes: Ingestion, inhalation, and dermal contact (Domenech and Marcos, 2021). Ingestion is the most direct pathway, particularly through the consumption of seafood (Danopoulos *et al*., 2020). Studies have detected microplastics in mussels (Digka *et al*., 2018), oysters (Wootton *et al*., 2022), crabs (Zhang *et al*., 2021), and various fish species (Thiele *et al*., 2021), many of which are consumed whole. Once ingested, microplastics may cause localised toxicity in the gastrointestinal tract, inducing oxidative stress, inflammation, and alterations in intracellular signalling pathways in human-derived cell lines (KC *et al*., 2023)**.** Their small size facilitates cellular uptake and potential translocation into the liver, kidneys, and brain. Moreover, microplastics can leach into human tissues and contribute to chronic health effects, including neurotoxicity, gastrointestinal toxicity, nephrotoxicity, hepatotoxicity, and developmental disabilities (Ali *et al*., 2024).

Due to these concerns, removing microplastics from freshwater and marine ecosystems is essential. A combination of physical, chemical, and biological approaches is currently being explored to tackle the issue, as illustrated in Figure 4 (Gao *et al*., 2022). Figure 4 (a) illustrates physical filtration using sand and membrane technology, where microplastics are sequentially captured by the sand layer and subsequently by a fine membrane. Figure 4 (b) demonstrates adsorption-based removal, where microplastics are captured by adsorbent-loaded materials that bind the particles. Figure 4 (c) illustrates the application of a magnet, which has the ability to attract certain microplastics from the environment. In Figure 4 (d), coagulation is depicted, where chemical coagulants cause microplastics to aggregate and settle out of the solution. Figure 4 (e) highlights photocatalytic degradation, where oxidation catalysts, activated by sunlight, break down microplastics into smaller, less harmful molecules. Lastly, Figure 4 (f) illustrates biodegradation by specific microorganisms or microbiota that metabolise microplastics, ultimately converting them into carbon dioxide, water, and other benign end-products. These technologies offer complementary pathways for mitigating microplastic pollution in aquatic environments, although their efficiency, scalability, and environmental impacts may require further investigation to support practical and sustainable deployment.

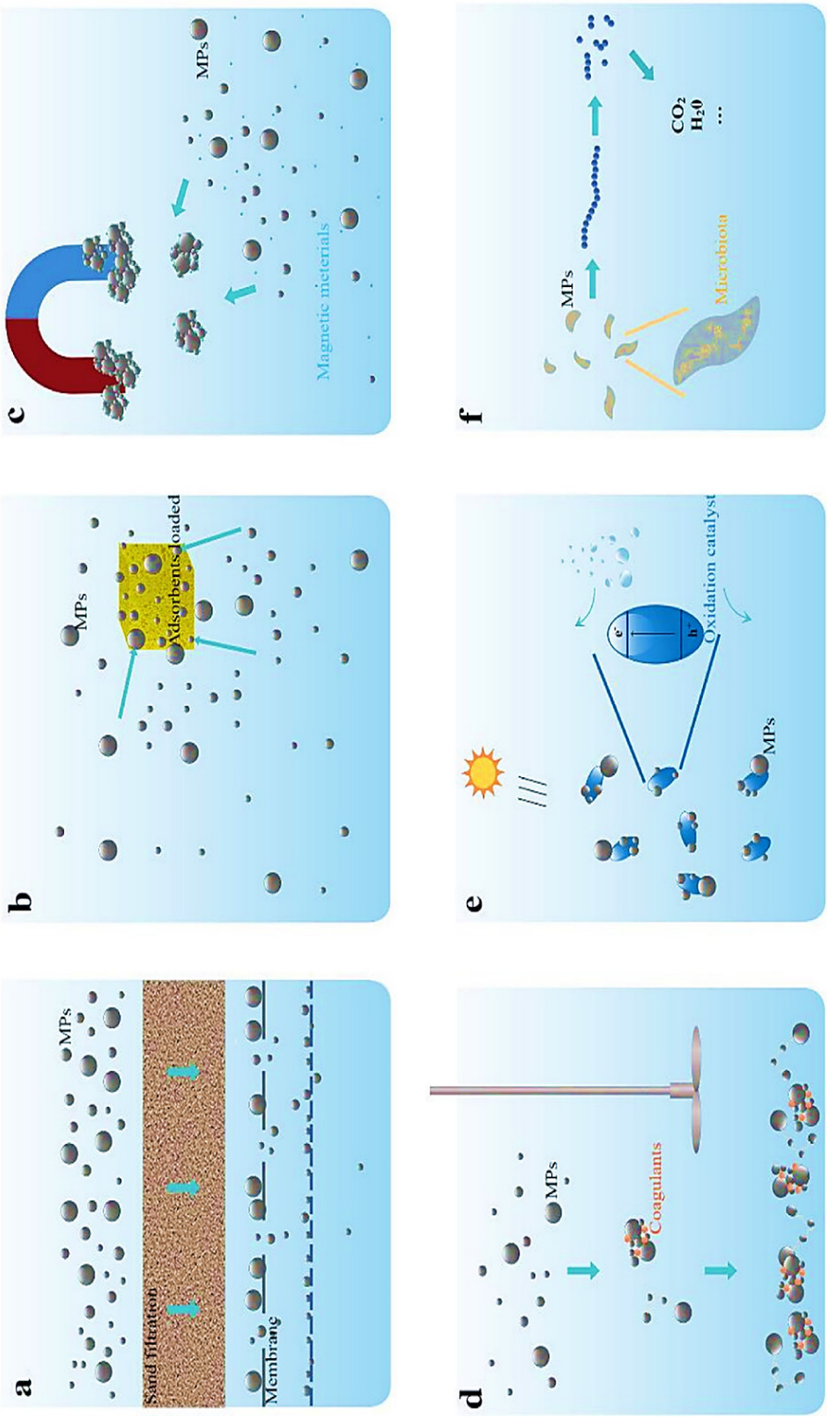

Figure 4. Schematic diagrams of main technologies for sorting and removing microplastics from water. (a) Filtration technology, (b) adsorption removal, (c) magnetic removal, (d) coagulation treatment, (e) photocatalysis and (f) biodegradation treatment

Source: Gao *et al.* (2022)

Conclusions

The widespread distribution of plastics and microplastics in freshwater and marine ecosystems has emerged as one of the most pressing environmental challenges in the 21st century. Driven by exponential increases in global plastic production and inadequate waste management, plastic debris now permeates nearly every aquatic niche, from urban rivers to remote lakes, mountains, and even oceanic trenches. The degradation of macroplastics into microplastics adds a further layer of complexity, introducing particles that are nearly impossible to detect or remove. The evidence presented in this study clearly shows that microplastics are pervasive across diverse geographical and ecological settings.

Microplastics pose ecological risks to aquatic organisms through ingestion, entanglement, and physiological harm, and in humans, they raise significant health concerns. Their presence in seafood and drinking water, along with their capacity to leach hazardous additives and adsorb toxic contaminants, has been linked to inflammation, organ toxicity, and even potential carcinogenic effects. Despite the growing awareness of these threats, existing wastewater treatment technologies and environmental management systems remain insufficient to intercept or fully remediate microplastic pollution. Addressing this multifaceted crisis will require an integrated approach that includes upstream interventions such as limiting plastic production, promoting biodegradable alternatives, and strengthening regulations on industrial emissions alongside downstream strategies like enhancing filtration technologies, investing in bioremediation research, and deploying nature-based solutions. Furthermore, public education and international cooperation are crucial for initiating behavioural change and implementing effective global policies. Only through coordinated, cross-sectoral action can we mitigate the ecological and human health impacts of plastic pollution and protect the integrity of aquatic ecosystems.

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