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Review

Microplastics in water resources: Global pollution circle, possible technological solutions, legislations, and future horizon

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HIGHLIGHTS

- Perceived risks from transporting MPs and the way it impacts freshwater.
- Addressing the need for considering the effects of multiple factors on adsorption of pollutants by MPs.
- The continued need for environmental research, awareness, and legislation against MPs
- Pinpointing main key factors governing the behavior and collection of MPs in the environment.
- The importance of evaluating risks in the complex process of pollutant adsorption

GRAPHICAL ABSTRACT

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ABSTRACT

Beneath the surface of our ecosystems, microplastics (MPs) silently loom as a significant threat. These minuscule pollutants, invisible to the naked eye, wreak havoc on living organisms and disrupt the delicate balance of our environment. As we delve into a trove of data and reports, a troubling narrative unfolds: MPs pose a grave risk to both health and food chains with their diverse compositions and chemical characteristics. Nevertheless, the peril extends further. MPs infiltrate the environment and intertwine with other pollutants. Worldwide, microplastic

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Ecosystem
Living organisms
Toxin scavenging

levels fluctuate dramatically, ranging from 0.001 to 140 particles.m^{-3} in water and 0.2 to 8766 particles.g^{-1} in sediment, painting a stark picture of pervasive pollution. Coastal and marine ecosystems bear the brunt, with each organism laden with thousands of microplastic particles. MPs possess a remarkable ability to absorb a plethora of contaminants, and their environmental behavior is influenced by factors such as molecular weight and pH. Reported adsorption capacities of MPs vary greatly, spanning from 0.001 to 12,700 μg·g^{-1}. These distressing figures serve as a clarion call, demanding immediate action and heightened environmental consciousness. Legislation, innovation, and sustainable practices stand as indispensable defenses against this encroaching menace. Grasping the intricate interplay between microplastics and pollutants is paramount, guiding us toward effective mitigation strategies and preserving our health ecosystems.

1. Introduction

Microplastics (MPs) are microscopic chemical particles (≤5 mm in size) existing in different shapes, composition, and morphology, which are mainly triggered by the breakdown of larger plastic articles, synthetic textile wears, personal care products, cosmetics, and deliberate plastic pellet release (European Environment Agency, 2023). Over the past century, the surge in plastic production and consumption, based on statistics on global production of plastics, has swelled from just 20 million tons in 1950 to about 460 million tons in 2019, which means that a total of 8.3 billion tons of plastics have been produced to date (OSPAR, 2021). If this production rate continues, the total amount of plastic produced may rise to 26 billion tons of plastic waste, of which an estimated 12 billion tons end up in the environment (Geyer et al., 2017). Available data shows that plastic consumption is closely related to Gross Domestic Product, briefly GDP ($p < 0.001$) (World Bank Open Data, 2022), meaning that developed countries produce the biggest share of microplastic waste (Fig. 1).

However, analysis of available data on MPs pollution shows that mismanagement of plastic waste, regardless of the amount of use, is increasing in areas with low awareness of pollution risks and a lack of regulatory legislation (Fig. 2).

This demonstrates the importance of public awareness and engagement in an effort to combat microplastic pollution. Re-evaluating plastic production and consumption is crucial to address the MPs issue. Non-exhaustive calculations estimate that current plastic production would need to decline by 46 % as targeted by the Pacific Environment Strategy (Chen et al., 2023) or, at best, by 70 % as targeted by Eunomia and Zero Waste Europe (Brooke et al., 2022) to maximize the impact of plastic on human health and the environment, Fig. 3.

However, like many other anthropogenic impacts, their ecological consequences will continue for centuries even if production is minimized or/stopped. The ubiquitous presence of MPs in our daily lives is driven by the numerous benefits of plastics, such as their use in packaging, cosmetics, and vehicles, because of their promising characteristics, such as low density, durability, and affordability.

MPs enter the aquatic environment through various routes, including sewage discharge, stormwater runoff, atmospheric deposition, and agricultural practices (Premakumara et al., 2014). For example, most litter on Australian beaches, including plastics, washes in from suburban streets via stormwater drains (Randwick City Council, 2022). These sources carry all types of plastics into the environment, including microbeads, synthetic fibers, and fragments created over time by the breakdown of larger plastics due to environmental factors such as weathering (Gan et al., 2023). A regional survey ascertains their migration in all possible size, shape, morphology, and composition to the sediments of the lakes (Yang et al., 2022) to the soil (Guo et al., 2020) and even their long-rage migration to the polar regions (Obbard, 2018). A frame-to-frame global pollution cycle of MPs is illustrated in (Fig. 4).

Once in the environment, MPs can persist for hundreds to thousands of years, with non-surface plastic potentially even longer. It is widely believed that all plastics introduced into the environment still exist today, either as intact or as fragments (Shen et al., 2020). Along with

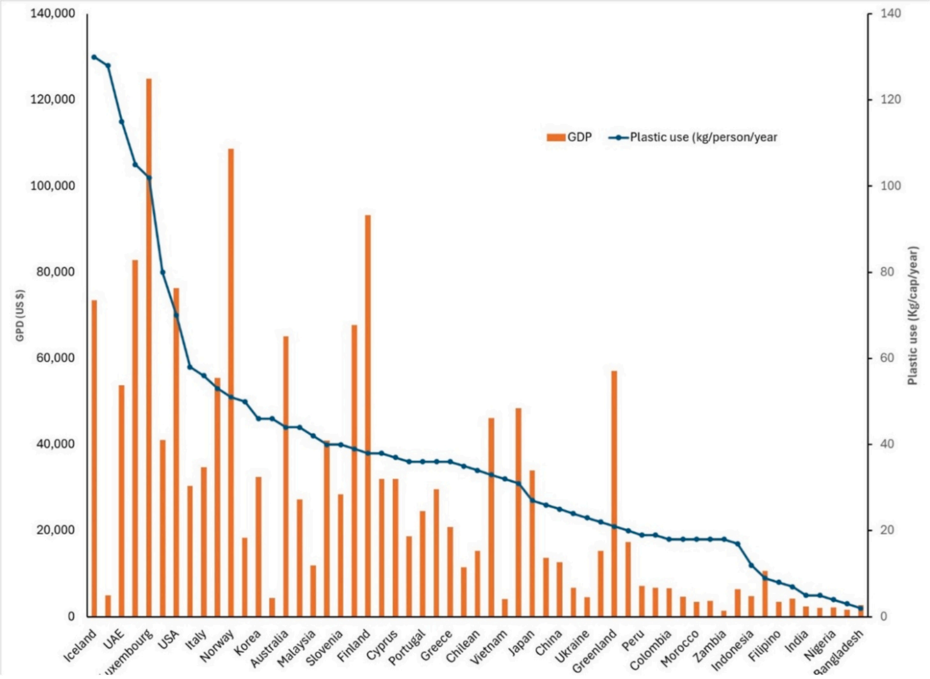


Fig. 1. Correlation between the GDP and plastic use for topmost countries.

increased lifespan, numerous marine organisms face heightened risks from plastic debris, including ingestion and entanglement. The global pollution risks caused by MPs have severe repercussions for marine ecosystems, human health, and food security. These minuscule particles can accumulate in the environment and be consumed by aquatic creatures, leading to a wide range of physical, chemical, and biological consequences (FAO, 2023). MPs can also carry pathogens, invasive species, and persistent organic pollutants (POPs) (Joo et al., 2021; Liu et al., 2022a). Through contaminated water, food, and air, each person is exposed to approximately 39,000 to 52,000 microplastic particles from various food sources every year (Cox et al., 2019). This number can rise sharply to 74,000 particles when other sources, such as inhalation, tap water, and plastic utensils, are taken into account (Kurniawan et al., 2024; Ziani et al., 2023).

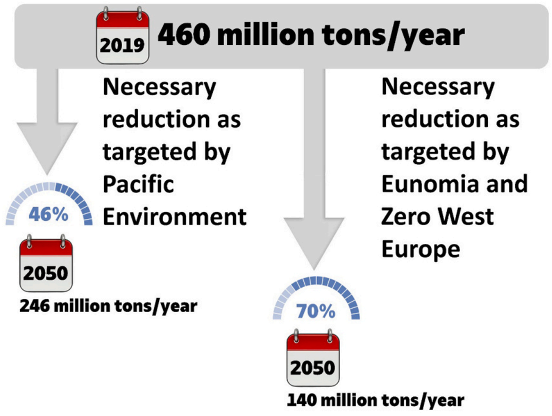
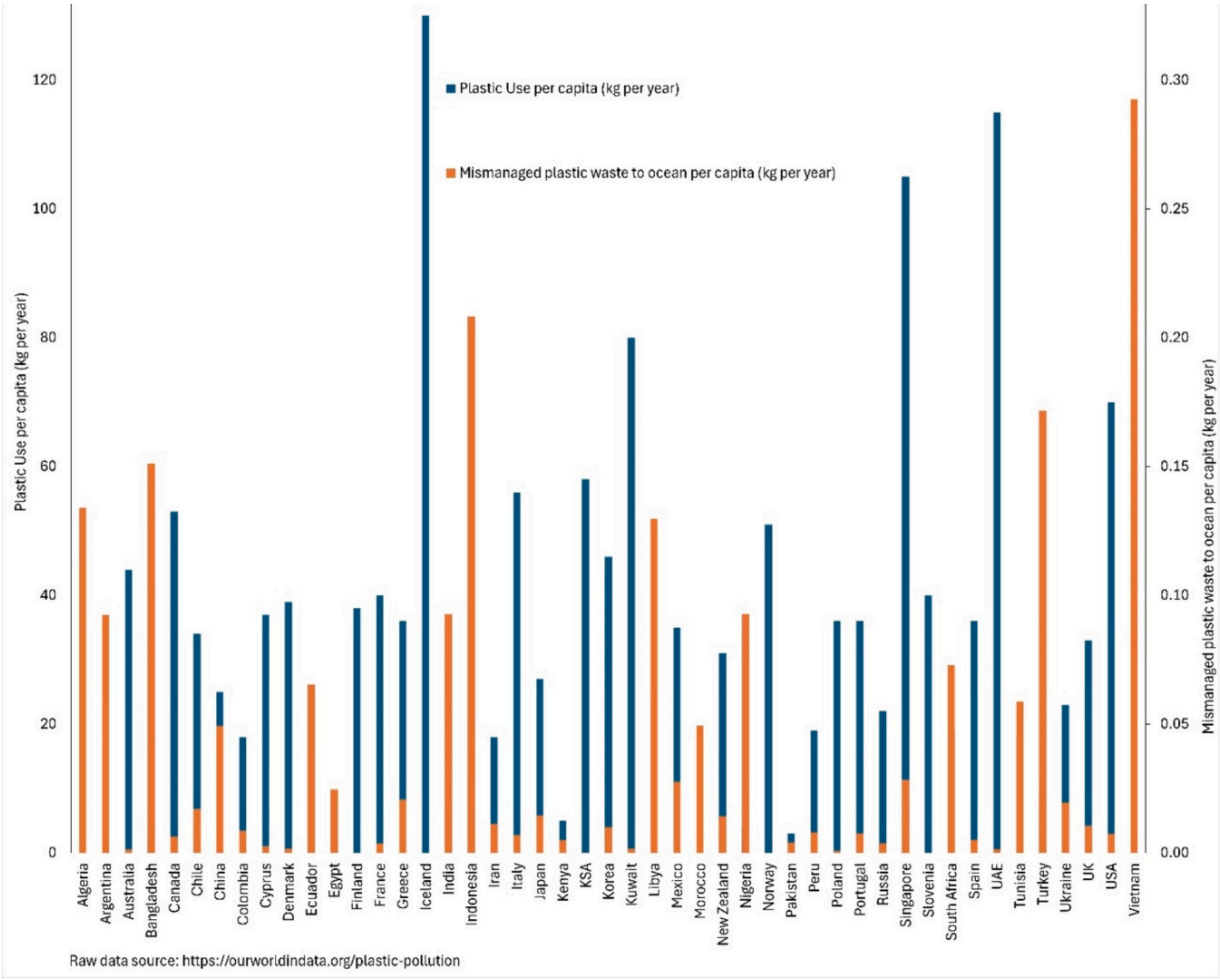


Fig. 3. Necessary reduction of plastic production to achieve target limits by 2050 as projected by Pacific Environment and Eunomia and Zero Waste Europe (Designed by the authors of the present work).

MPs in ecosystems can jeopardize numerous organisms, including plankton, invertebrates, and vertebrates, resulting in unforeseen consequences (Wu et al., 2020). Adsorption, aggregation, uptake/reuptake, and release of chemicals represent potential mechanisms for transporting POPs and metals. Several studies confirm evidence of direct effects of these chemicals on living organisms. For example, MPs were found in the gastrointestinal tracts of 36.5 % of the samples of 10 fish species from the English Channel (Lusher et al., 2013). In southern New Zealand, >75 % of fish have ingested MPs, with an average of 2.5 individual particles per fish (Clere et al., 2022). The toxicity of low-density poly-ethylene (LDPE) and polyethylene terephthalate (PET) was seen in Daphnia in terms of reduced reproductive activity and irregular heart rate (Sana, 2024). Another study showed that MPs can



Raw data source: https://ourworldindata.org/plastic-pollution

Fig. 2. Correlation between the plastic use worldwide and mismanagement of plastics wastes.

Fig. 4. Frame-to-frame global pollution cycle of MPs, including sources or origins (a), type, size and distribution of particles (b), migration to the environment (c), introduction to agro-food chains (d), scattering and sedimentation in the water, soil, and air (e), introduction to life cycle and body of human beings (f), uncontrolled distribution worldwide (g), and even beyond the imagination of human beings, space pollution (h) (Designed by the authors of the present work).

affect rotifer community structure in natural water bodies (Reyes-Santillán et al., 2024). Polypropylene and polystyrene have been found to cause DNA damage and inhibit the action of the enzyme acetylcholinesterase (AChE) in freshwater snails, impairing their ability to detect the presence of predators in their environment (Sapkale and Pandit, 2023). In addition, one worrying aspect of MPs pollution is the aesthetic issue of urban, coastal, and ocean litter, which has escalated into a global crisis, causing harm to ecosystems and living beings (Gautam et al., 2023). Yearly surveys of coastlines, lakes, and oceans reveal decreasing average plastic particle size and a rise in MPs fragment abundance and global distribution (Beiras and Schönemann, 2020) (Fig. 5).

The link between MPs and other chemical contaminants poses a significant threat to the environment and life cycles of plants, animals, and human beings. Several studies have demonstrated the ability of plastics to absorb, concentrate, and carry POPs in the marine environment (Adegoke et al., 2023; Lubchenco and Haugan, 2023; Okoye et al., 2022). For instance, high mortality was observed among the treatment groups of Daphnia when MPs were combined with other environmental pollutants (100 % mortality rate for LDPE+Pb and <60 % for PET+Fe). This synergetic action increases the hazard to the environment, humans, and wildlife and highlights the importance of considering synergistic effects when assessing the toxicity of emerging contaminants. Subsequently, assessing the impact of MPs in the context of multiple stressors will lead to more realistic results. Fig. 6. depicts MPs' path from consumption to environmental release. The human body acts as the intersection point for both MP intake and elimination.

To combat the MP's pollution, we must adopt strategies across

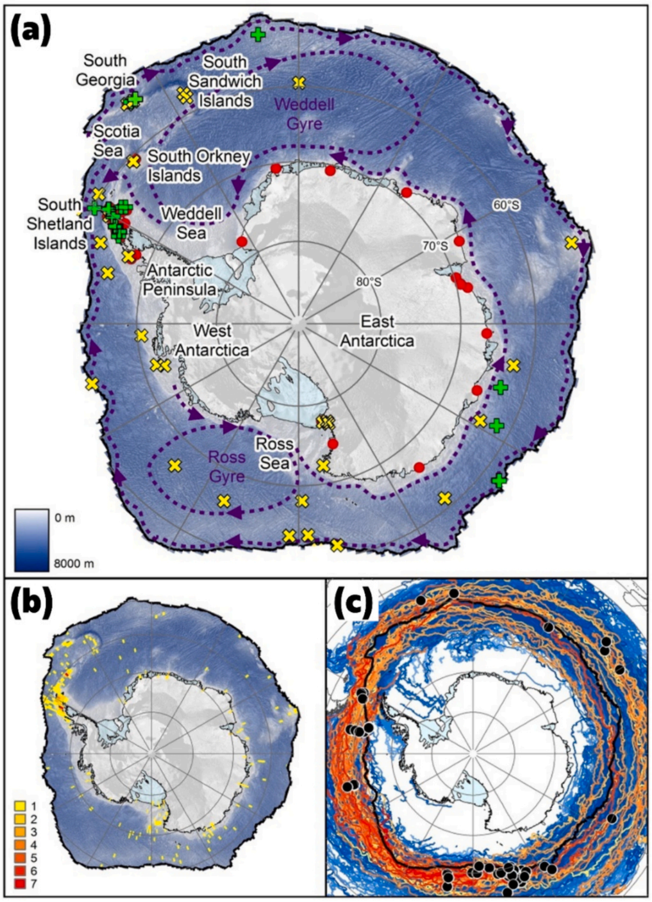


Fig. 5. Key insights into Antarctica's coastal infrastructure, plastic pollution data, ship presence, and ocean drift patterns: (a) National Antarctic Program-managed coastal facilities in the Antarctic region have documented the presence of MPs in surface waters, along shorelines and within sediments situated south of the Polar Front. The map illustrates the average location of the Polar Front, clearly demarcated within the plot boundary. Research stations and facilities are marked with red dots, while yellow crosses indicate the presence of MPs, and green crosses denote the detection of MPs. The major ocean currents' flow is visually depicted using purple arrows. (b) Maps the average ship density in a 1° × 1° grid cell from November 2009 to January 2010, using data from the EU maritime forum. (c) Displays drifters' paths, 1989–2015, south of 48°S. Highlights drifters deployed north of the Polar Front (black line) and moved south, marked in red/orange. Black circles indicate their deployment spots (Waller et al., 2017), Elsevier copyright (2017).

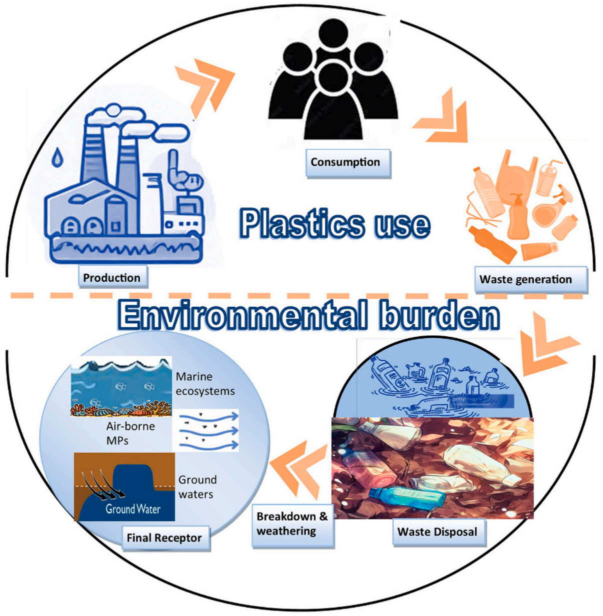


Fig. 6. Schematic illustrating the flow of plastic materials from human consumption to their release into the environment. Human bodies are unavoidably a spot where plastic materials enter and exit (Designed by the authors of the present work).

product lifecycles, such as enhancing design, improving waste management and recycling, and raising consumer awareness (Khan et al., 2019). These strategies should aim to establish a comprehensive, integrated, and affordable management system that prioritizes environmental protection and public health. Policy tools like standards, incentives, and regulations for manufacturers and consumers can help mitigate the MPs' pollution.

Different aspects of plastic pollution have been addressed in several review articles, including sources and distribution, e.g., (García Rellán et al., 2023; Kurniawan et al., 2023a), environmental impacts, e.g., (Emenike et al., 2023; Kadac-Czapska et al., 2024), detection and analytical methods, e.g., (Dong et al., 2023; Soursou et al., 2023), human health impacts, e.g., (Sun and Wang, 2023; Winiarska et al., 2024), mitigation and remediation, e.g., (Agbasi et al., 2024; Rani et al., 2024), food chain contamination, e.g., (Eze et al., 2024; Mamun et al., 2023), technological innovations, e.g., (Calero et al., 2021; Spreafico and Russo, 2023), legislation and policy, e.g., (da Costa et al., 2020; Lam et al., 2018), public awareness and behavioral change, e.g., (Hossain, 2024; Praveena, 2024), and socio-economic impacts e.g., (Gunawan et al., 2021). Compared to marine systems and oceans, the number of studies on MP's contamination in freshwater systems (all non-marine water-based ecosystems, including rivers, lakes, ponds, glaciers, and snow deposits) is still insufficient (Citterich et al., 2023; Samani and Meunier, 2023). The focus of review articles on various aspects of MP's pollution is shown in Fig. 7.

This review offers a comprehensive approach to MP's pollution. It integrates a discussion of environmental impacts with an analysis of global legislative measures, an assessment of their effectiveness, and the provision of policy recommendations based on empirical evidence. It also explores technological solutions to microplastic pollution through detailed case studies and practical insights. Furthermore, the article delves into the fate of MPs, including their accumulation in the environment and their impacts on freshwater organisms and structure. In addition, a detailed classification system for MPs takes into account the latest scientific findings and new categories. A clear and informative classification of MPs is missing from current reviews. This comprehensive approach, integrating taxonomy, legislation, and technology, addresses significant gaps in the current literature and provides a holistic understanding and perspective of microplastic pollution.

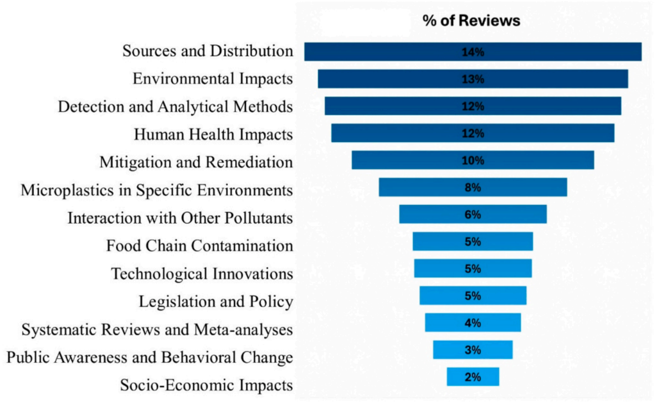


Fig. 7. Focus of published review articles on different aspects of plastic pollution (Designed by the authors of the present work).

2. Classification of MPs

Plastic materials can vary in properties like hardness, elasticity, and moldability through polymerization, which involves chemical reactions. Key factors include the initial materials, production process, and additives like plasticizers (e.g., BPA, BPS), adhesion promoters, flame retardants, or color pigments. Knowledge of plastics classification is vital for efficient disposal or mitigation. Clear classification helps one to (i) identify the source of plastics, (ii) better assess their potential risks to human health and the ecosystem, and (iii) develop mitigation strategies based on their chemical properties. Plastics can be classified into three main categories: (1) composition-based classification, (2) size-based classification, and (3) shape-based classification.

2.1. Composition-based MPs classification

MP may be categorized by the type of bonding of molecular chains, which can be linear, branched, cross-linked, or entangled. The macromolecular bonds can be chemical or physical, classifying them as thermoplastics, elastomers, or thermosets (Mohamadi, 2023).

2.1.1. Thermoplastics

Thermoplastics are typically linear or slightly branched and exist disorderly and tangled. Chemically, thermoplastics can be categorized into two groups, i.e., amorphous and semi-crystalline. Semi-crystalline thermoplastics are characterized by increased hardness, stability, and resistance to chemicals. As the number of crystallites rises, thermoplastics become progressively harder and more brittle (Luo et al., 2022). Examples of thermoplastics include polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polyamide (PA), polystyrene (PS), polycarbonate (PC), polybutylene terephthalate (PBT), and polyvinyl chloride (PVC). There is a wide range of products made from thermoplastics, such as sports equipment, toys, drinking bottles, food storage containers, bullet-proof vests, plastic grocery bags, and shampoo bottles (Proto Plastics, 2019). The most common MPs in the sediments of the Bay of Brest in the North Atlantic were PE (53.3 %) and PP (30 %) (Frère et al., 2017). A similar composition of MPs was also found in the surface waters of the same area (67.4 % PE and 16.5 % PP) (Frère et al., 2017). The same trend was also found in the sediments of the Venice Lagoon, where the MPs were dominated by PE (48.4 %) and PP (34.1 %) (Vianello et al., 2013). In the sediments of the detected black, MPs were mainly of PE or PP (44.5 %), followed by PA (32 %) (Cincinelli et al., 2021).

2.1.2. *Elastomers*

Elastomers are cross-linked with wide-mesh covalent bonds. They are insoluble and non-meltable and form a flexible, entropic chain structure resembling a polymer ball at room temperature, stretching under load and returning to its original shape when unloaded (Liu et al., 2017). These compounds offer the stretchiness of rubber and the shaping ease of thermoplastics so that they can be processed into almost any shape. Examples of products include toys, toothbrushes, medical tubes, sealants, sports equipment, tires, and additives in adhesives and lubricants (Kuraray Europe GmbH, 2021).

2.1.3. *Thermosets*

Thermosets, on the other hand, have a dense network of intermolecular covalent bonds, resulting in an amorphous, highly temperature-resistant structure (Fan and Njuguna, 2016). They are hard, non-melting, and non-plastically deformable after curing. Thermosets possess properties such as electrical insulation and chemical resistance. Examples of thermosets include polyurethane, urea-formaldehyde, and vinyl esters (Fan and Njuguna, 2016). Various finished products can be made of thermosets, such as fabrics, mattresses, thermal insulators, hospital articles, adhesives, tires, shoes, etc. (Polyexcel, 2021).

2.2. *Size-based MP's classification*

Several properties of MPs are directly or indirectly related to their size. Comminution, a process that alters the surface structure of plastics, can lead to changes in their properties. This includes increasing the specific surface area and reducing size, which can subsequently impact adsorption (Keskin et al., 2019). Different-sized plastic particles have varying effects, with smaller particles having the potential to accumulate in tissues and disrupt crucial biological functions (Campanale et al., 2020; Chen et al., 2009). MPs can be sorted based on their size and dimensions, from primary to secondary.

2.2.1. *Primary MPs*

Primary MPs come in various forms, like granules and powders (Issac and Kandasubramanian, 2021). Primary MPs are also termed “unweathered MPs” as they do not originate from natural weathering or abrasion. They are crafted at the micro or nano scale to fit specific applications like personal care products, textiles, medicines, and more (Alvim et al., 2020; Strungaru et al., 2019). These MPs are transported into the environment along with wastewater through households, factories, and sewage systems. Due to their minuscule size, wastewater treatment facilities are unable to effectively remove all primary microplastic fragments (Auta et al., 2017). MP's fragments, employed in industry as raw materials for plastic goods, contribute to environmental MP's pollution. MPs pose several challenges in wastewater treatment due to their size, < 5 mm, which traditional methods struggle to remove effectively. MPs can disrupt biological treatment, like activated sludge systems, by acting as a substrate for microbial growth, potentially impeding organic matter and nutrient treatment (Al-Hazmi et al., 2023a; Derwis et al., 2023).

Additionally, some MPs are generated during treatment from the breakdown of larger plastic materials in wastewater, further increasing the MPs load in treated effluent and potentially endangering aquatic ecosystems when released into water bodies. Due to their minuscule size, wastewater treatment facilities cannot effectively remove all primary MP fragments (Auta et al., 2017). Thus, MPs in wastewater can hinder water reuse in the industry and agriculture sectors (Al-Hazmi et al., 2023d). In order to tackle this issue effectively, it was imperative to implement source control measures and enhance pre-treatment procedures. Additionally, the adoption of advanced treatment technologies like integrating anammox-based systems with nanofiltration and/or nanoparticles was essential (Al-Hazmi et al., 2023b, 2023c; Khan Khanzada et al., 2023a). Furthermore, a sustained dedication to research is necessary to overcome the challenges posed by these tiny contaminants in wastewater systems.

2.2.2. *Secondary MPs*

Secondary MPs stand as the dominant source of environmental MPs and arise primarily from the breakdown of larger plastics. In mechanical fractures, weathering processes like erosion from sand or other rough surfaces can break plastic into smaller pieces, increasing their surface area. These minute plastic fragments have been steadily accumulating in our oceans over the course of decades. They exhibit distinct characteristics compared to primary MPs, such as variations in roughness, oxygen content, and specific surface area. The surge in secondary MPs in aquatic environments is mainly caused by extensive weathering and environmental factors.

In mechanical fractures, weathering processes like erosion from sand or other rough surfaces can break plastic into smaller pieces, increasing their surface area. This, in turn, boosts their ability to adsorb pollutants (Yu et al., 2019). Chemical degradation, such as acid or alkali hydrolysis, as well as biodegradation by organisms like waxworms, mealworms, and certain microbes, along with UV degradation from exposure to UV radiation, can alter the chemical properties of plastic waste (Waller et al., 2017). Fragmentation also depends on factors like temperature and UV radiation levels (Li et al., 2016).

2.3. *Shape-based MP classification*

Based on their shape, MPs can also be classified into various types, such as microfibers, nurdles, fragments, microbeads, films, foam, and pellets, among others.

2.3.1. *Microfibers*

Microfibers are a specific type of MPs that come from synthetic textiles such as polyester, nylon, and acrylic. These tiny fibers are shed during the washing and wearing of clothes made from these materials and enter the environment through wastewater. A proposed definition describes microfiber pollutants as: “any natural or artificial fibrous materials of thread-like structure with a diameter less than 50 μm, length ranging from 1 μm to 5 mm, and length to diameter ratio greater than 100” (Carney Almroth et al., 2018; Frias and Nash, 2019). A general definition considering the size, shape, and color of microfibers is still lacking. Natural microfibers include wool, silk, cotton, and flax, while synthetic ones encompass polyolefin, nylon, acrylic, and polyester. Regenerated cellulosic fibers like triacetate, diacetate, and bamboo are also classified as microfibers (Liu et al., 2019b). Studies showed that microfibers are the most common type of microplastic in the environment (Álvarez et al., 2018; Galvão et al., 2023). In the process, about 700,000 fibers are dissolved in a wash cycle of 6 kg of clothing containing MPs as fibers (Napper and Thompson, 2016)

2.3.2. *Nurdles*

Nurdles, commonly referred to as mermaids' tears, are tiny plastic pellets with a mass of about 20 mg apiece and a diameter of typically less than 5 mm (Hammer et al., 2012). After production from petrochemical precursors, nurdles are shipped or transported by train, melted, and formed into the finished product. They are the foundation for manufacturing all plastic products, from vehicle parts to bottles. Marine creatures, like seabirds and fish, are at risk of ingesting nurdles due to their small size and translucent color, which can resemble fish eggs (Sewwandi et al., 2023).

2.3.3. *Fragments*

Fragments result from the disintegration of plastic products. These fragments subsequently deteriorate into micro- and nanoparticles that can no longer be separated from sand grains (Vasseghian et al., 2023a; Zhang et al., 2023). Theoretically, a bag made of two plastic sheets measuring 50 cm by 40 cm by 50 μm in thickness might produce 20 trillion fragments with a volume of 1 nm^3 (Gerritse et al., 2020; ter Halle et al., 2016). Further fragmentation can also be undertaken by the microscopic crustaceans, which can break down MP into fragments with dimensions no bigger than a living cell during the first 24–96 h of uptake (Hasegawa and Nakaoka, 2021; Mateos-Cárdenas et al., 2020). These findings highlight the overlooked role of biochemical processes in MP disintegration. Aging reduces specific surface area and heat resistance but enhances hydrophilicity and oxygen-containing functions (Yan et al., 2023). These fragments are hard to manage and are a key subject for more research because they are widespread in our biosphere and could affect human well-being.

2.3.4. Microbeads

Microbeads are plastic constituents (mostly made from polyethylene, polystyrene, and polypropylene) added to cosmetic products such as hand sanitizer, soap, shampoo, etc., cleansing or exfoliating agents. They are small particles no larger than 5 mm in size, and they come in different colors and shapes (Kumar et al., 2021). Alternative descriptors like microspheres, nanospheres, or mermaid tears have also been found to be useful (Hunt et al., 2021; UNEP, 2015). These products have been recognized as a hazardous wellspring of MPs in the environment as they can reach various water bodies and sediments due to current sewage treatments' inability to eliminate them completely (Ding et al., 2020; Sallan et al., 2023). Microbeads have garnered significant global attention for their proven harmful effects on the environment, particularly aquatic ecosystems (Silviana et al., 2022; Zhu et al., 2019). The persistent quality of microbeads, resistant to biodegradation, fosters their accumulation in both the environment and biological systems. Consequently, this elevates the potential toxicity levels for living organisms and humans (Miraj et al., 2021) (Fig. 8).

3. Factors affecting the behavior of MPs in the environment

The chemical and physical properties of MPs, as well as environmental factors, control the fate of MPs and how they behave in the environment. For example, the equilibrium dissociation constant (Kd) can predict MPs' adsorption capacity. A lower Kd signifies stronger binding affinity between the MPs and their target, indicating a higher capacity of MPs to adsorb other pollutants (Rainsford et al., 2023). DDT sorption on PVC (Kd value of 104.785 ± 14.985 L/kg) was slower than DDT sorption on PE (Kd value of 96,892 ± 20,529 L/kg) (Bakir et al., 2012). Other observations showed that the amount of contaminant sorbed to MPs depends more on the sorption affinity than its initial concentration in the water (Tourinho et al., 2019). A growing body of research indicates that globally collected plastic waste contains detectable organic pollutants (Bajt, 2021; Catarci Carteny et al., 2023; Lyu et al., 2024).

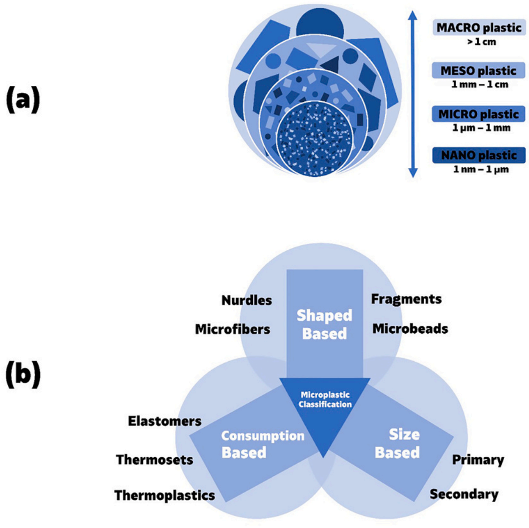


Fig. 8. Classification of microplastics: (a) based on size (b) based on shape and composition. The multiplicity of type, shape, size, and chemistry of particles underlines the complexity of processes by which they can be separated from the ecosystem (Designed by the authors of the present work).

Nevertheless, studies on the distribution behavior of organic compounds in plastics are still scant, with only a few available, and our understanding of factors influencing sorption/desorption remains insufficient. For example, the importance of dietary intake versus other exposure routes has not been fully explored, leading to potential serious consequences. Environmental influences, including specific surface area, crystallinity, and oxygen-related functional groups, have impacted MP attributes (He et al., 2023). These factors are crucial to consider during adsorption processes, as they enhance the capacity of MPs to adsorb pollutants (Yu et al., 2019).

Salinity, the amount of salts dissolved in water, and humic acid can affect the association of the MPs with other particles, including organic matter and pollutants. In high-salinity environments (e.g., oceans), MPs may aggregate more easily and sink faster compared to lower-salinity environments (e.g., freshwater lakes) (Wu et al., 2019). Salinity can also affect the surface charge of MPs, which, in turn, affects their interactions with other charged pollutants (Liu et al., 2022b). For example, PHE adsorption onto MPs increased with increasing salinity (Zhang et al., 2020a). However, adsorption of PFAS on MPs (e.g., HDPE) decreased as salinity increased (70 % adsorption of PFHxA on HDPE in freshwater vs. 20 % adsorption of PFHxA on HDPE in seawater) (Llorca et al., 2018). This indicates that salinity's role is a double-edged sword and that the interaction between pollutants and POPs is more complex than it appears and involves many factors such as i) the type of the MP and pollutants adsorbed, ii) the initial concentrations of both MP and pollutants and iii) the pH of the water body. The effect of salinity is related to pH. As is known, high salinity stabilizes water conductivity due to improved buffering capacity. The pH, in turn, affects the surface charge of the MPs and their behavior in the environment (Rahman et al., 2023).

Water currents and winds can also affect the extent of interaction between MPs and the surrounding environment. Large water currents act as conveyor belts, transporting MPs over long distances (Kane and Clare, 2019). Trapped MP debris within these streams can accumulate in specific areas, forming plastic litter patches where concentrations are much higher compared to other areas. On the other hand, wind-driven surface currents move marine MPs closer to the water surface and along coastlines, resulting in beach pollution (da Costa et al., 2017). Upwelling and downwelling currents affect the vertical distribution of MPs in the water column (Díez-Minguito et al., 2020). Wind can also directly transport air-suspended agents and lightweight agents on the surface of the water. This wind-driven transport can carry deputies over long distances, allowing them to reach remote locations such as mountain ranges or even polar regions. However, it should be noted that these factors often work together to influence the movement and distribution of MPs. Water temperature and salinity can also affect MPs' interactions with the aquatic environment. For example, due to its lower density, warm water can cause some MPs to float, while cold water can cause them to sink (D'Avignon et al., 2022). This temperature-dependent buoyancy can affect the vertical distribution of MPs in the water column. Temperature can also affect the adsorption and desorption of contaminants on MPs. Higher temperatures may increase the desorption rate, resulting in the release of pollutants back into the environment (Hartmann et al., 2017).

Fragmentation is another important factor. Fragmentation of MPs can be initiated by environmental, chemical, biological, or physical processes, including ultraviolet exposure, oxidants, hydrolysis, and physical shearing (Gerritse et al., 2020; ter Halle et al., 2016; Zhang et al., 2021). Millions of fragments can result from the disintegration of a single plastic bag. These fragments subsequently deteriorate into micro- and nanoparticles that can no longer be separated from sand grains (Al-

Hazmi et al., 2024b; Zhang et al., 2023). Theoretically, a bag made of two plastic sheets measuring 50 cm by 40 cm by 50 μm in thickness might produce 20 trillion fragments with a volume of 1 nm^3 (Gerritse et al., 2020; ter Halle et al., 2016). The morphology of plastics is substantially impacted by further fragmentation, which can break down MPs into fragments with dimensions no bigger than a living cell (Hasegawa and Nakaoka, 2021; Mateos-Cárdenas et al., 2020). These fragments are complicated to control and an essential topic for further investigations due to their prevalence in our biosphere and potential impacts on human well-being.

MPs aging reduces heat resistance and surface area while improving hydrophilicity and functionalization with oxygen groups (Liu et al., 2019a; Yan et al., 2023). This alteration in chemical properties affects how MPs interact with the surrounding environment. For example, the sorption capacities of PT and UF to PHE were greatly enhanced with aging (Zhang et al., 2020a). The preceding discussion highlights the complexity of MP interaction with the environment and several factors that influence this process, acting together either synergically or in opposing directions.

4. Impacts on ecosystems

MPs distribution in marine and coastal areas, including water, sediment, and biota, is estimated at levels from 0.001 to 140 particles/m^3 in water (Thushari and Senevirathna, 2020). When MPs are present in the marine environment, their fate and position (floating or sinking) are highly influenced by their chemical properties, such as structure and composition, as well as physical properties, such as density and size (Fig. 9). For example, high-density MPs such as PA, PS, PVC, and PES are expected to go down (Browne et al., 2007; Cole et al., 2011). However, although polypropylene and polyethylene are of low density and are expected to float, adding mineral fillers during production can make them too denser to float (Corcoran, 2015). on the other hand, MPs of Higher density may (re-)float or suspend and relocate within the water body as a result of turbulent and stormy conditions (Cole et al., 2011). Accumulation of microorganisms, known as biofouling, could increase the polymers' density, polling them to the bottom of the water column (Amaral-Zettler et al., 2021).

According to (Chubarenko et al., 2016), the process of MPs settling on the seafloor can take anywhere between 6 and 8 months for fibers and 15 years for spherical MP. MPs on the seafloor are protected from UV light, which delays the degradation of those materials (Corcoran, 2015).

Degradation of plastic can take place via several pathways, i.e., biological, photo-, thermal, mechanical, or hydrolysis (Chamas et al., 2020) (Fig. 10). When MPs are present under suitable conditions with moisture, oxygen, and naturally occurring microorganisms, the ester bonds of MPs are hydrolyzed, leading to their breakdown. During hydrolysis, MPs decompose into water, carbon dioxide, and a small amount of other elements, depending on the type of MP (Hung et al., 2012; Karamanlioglu et al., 2017). However, hydrolysis of MPs in aquatic

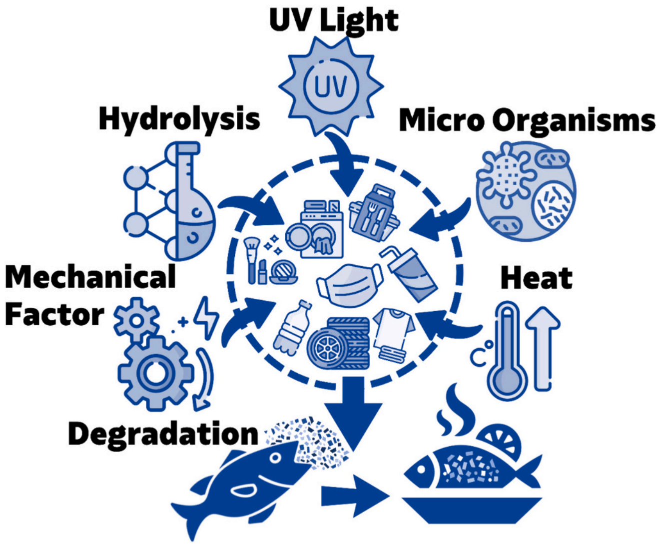


Fig. 10. Potential methods by which plastics degrade after being exposed to various environmental variables (Designed by the authors of the present work).

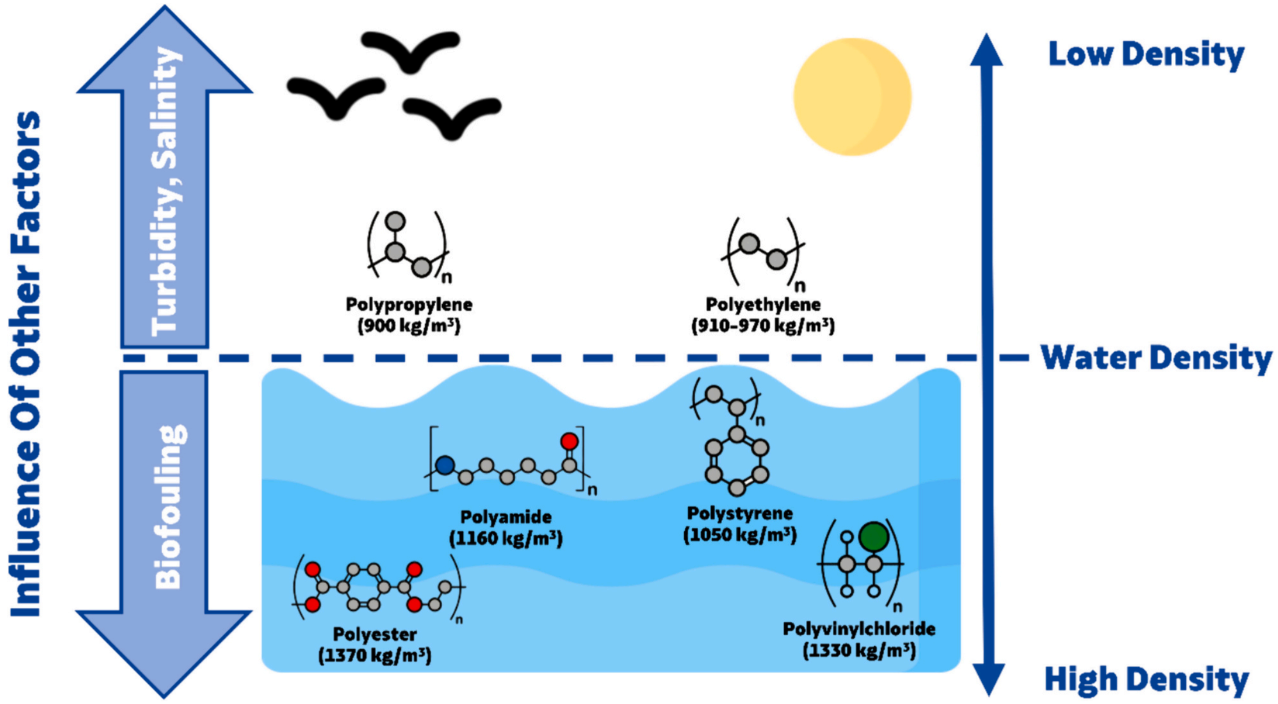


Fig. 9. Distribution of MPs in the water column depending on their physical and chemical properties (Anderson et al., 2016) (2016) (Re-designed by the authors of the present work).

environments is a slower process due to impedance caused by lower temperatures and oxygen levels, and, hence, plastic degradation on beaches is faster than in the water body (Viel et al., 2023).

The mechanical degradation of MPs depends on the strength of the plastic. While amorphous plastics have lower strength and fatigue resistance, semi-crystalline plastics like PE, PP, and PET have higher strength and resistance to fatigue. The material may become brittle due to excessive crystallinity, making it vulnerable to weather-related cracking and breaking. Aging and dispersion of MPs in water and its interactions with various species are influenced by increased crystallinity, which also correlates with a larger MPs density (Auta et al., 2017; Guo and Wang, 2019). Aging processes in MPs introduce oxygen-containing functional groups like —OH, C—O, and C—OH, leading to structural changes—initially, crystallinity increases in the surface layer where oxidation occurs. However, as weathering progresses, more crosslinking and chain scission reduce plastic mechanical properties. Discoloration of plastic debris as a result of oxidation could be attributed to its accumulation or the release of stabilizers from the plastic (Gautam et al., 2020).

However, although MPs undergo degradation under favorable conditions, the time required to mineralize plastics entirely is estimated to be some hundreds to thousands of years (Chamas et al., 2020). Thus, MPs can accumulate in various environmental compartments, such as oceans, rivers, lakes, soil, and sediments. On the other hand, as plastic particles continue to break down and fragment, their availability to various species in the oceans and food webs increases.

MPs were detected in organisms at six sites along the French-Belgian-Dutch coastline, with levels averaging 0.5 MPs/g in *M. edulis* and 0.4 particles/g in *A. marina* (Van Cauwenberghe et al., 2015). This ingestion raises concerns about transferring organic chemicals and metals through the food chain. Ingestion of MPs is associated with three harmful effects:

1) physiological/physical effects, which refer to MPs' shape, size, and concentration, are primarily due to ingestion with food/instead of food by living organisms (Pedersen et al., 2020). The more MPs are ingested, the more likely living things will undergo altered development or a change in dietary patterns (Horton et al., 2018).
2) lethal reactions due to releasing harmful chemicals such as plasticizers, antioxidants, flame retardants, dyes, and others used in plastic fabrication. Toxicity is increased by admixtures designed to adapt and improve the properties of the plastic for a particular use. These can be leached into the body tissues of living creatures and disrupt the endocrine system, affecting mobility and reproduction and causing cancer development (Yu et al., 2019). Toxicity can vary following the quantity of the additives for each plastic (Botterell et al., 2023);
3) harmful reaction due to pollutants uptake by MPs. The longer exposition time and hydrophobic nature favor the pollutant uptake by MPs.

Several factors, including disposal method, quantity, and meteorological conditions, govern the buildup of MPs in the environment. Tracking MP movement from mussels to crabs showed that the highest microsphere concentration in crab hemolymph was found after 24 h (15,033/ml), decreasing to 267 ml by day 21 (Farrell and Nelson, 2013). This peak amount represented only 0.04 % of the mussels' initial exposure. Small size and widespread distribution make them easily ingested by various biotas, with ingestion levels varying among different species (Ain Bhutto and You, 2022). The effect of MPs on diverse marine organisms, including bivalves, oysters, copepods, cladocera *Daphnia magna*, *Crepidula onyx*, collemoles, suspension feeders, fish, and seabirds has also been reported (Kibria et al., 2022).

The detrimental effects of MPs on zooplankton, like copepods, include impacting their feeding habits, fecundity, and overall functioning (Alfonso et al., 2023). Specifically, studies on the copepod Celanus helgolandicus, predominantly found in the Atlantic Ocean and a vital food source for many fish larvae due to its size, high lipid content, and abundance, have highlighted the adverse consequences of MPs ingestion (Rodríguez-Torres et al., 2020). When copepods consume polystyrene microspheres measuring 20 μm, their carbon biomass decreases by 40 %, resulting in an energy deficiency (Cole et al., 2015). This deficiency leads to a rapid depletion of lipids, which in turn impairs their growth and, ultimately, results in copepod mortality. Furthermore, prolonged exposure to MPs leads to the production of smaller eggs and reduced hatching rates (Chan et al., 2020; Ferrante et al., 2022).

The newly discovered Eurythenes plastics, an amphipod in marine habitats, got its name from plastic waste in its gut. A particle in its gut was 649.648 μm long and closely resembled polyethylene terephthalate, a polymer found in textiles, packaging, and bottles (Peng et al., 2020). This shrimp-like creature, measuring around two inches in length, resides 20,000 ft deep in the Pacific Ocean, highlighting plastic contamination in unexplored habitats. While the ecotoxicological impact of MPs on deep-sea amphipods remains understudied, it is likely that other undiscovered Pacific Ocean species at these depths may face similar risks from MPs ingestion (Cau et al., 2020; Jamieson et al., 2019). *Daphnia magna* (a crucial food source for various aquatic organisms) showed a high sensitivity to MPs, which makes them ideal test subjects to explore the toxic effects of MPs on marine organisms (González et al., 2023).

Glyphosate monoisopropylamine salt caused a mortality rate of 23.3 % when tested without MPs (Issac and Kandasubramanian, 2021). However, when MPs were introduced, a shift in toxicity was observed, with glyphosate acid exhibiting the highest mortality rate of 53.3 % with polyethylene beads and 30 % with polyamide fibers (Xin et al., 2023). This observation highlights MPs' negative and harmful role in enhancing the toxicity of other environmental contaminants. In the case of mussels exposed to MP, they lose their ability to grip surfaces due to a reduction in filament production. Mussels typically aggregate and form reefs, which serve as essential shelters and breeding grounds in aquatic ecosystems (Green et al., 2019).

MPs were shown to:

i) Interfere with the reproduction and hardening of oysters, causing a change in food intake and food distribution inside the oyster and a decrease in egg production, egg quality, sperm motility, and fertilization (Sussarellu et al., 2016).
ii) It produces a diminution in algae chlorophyll contents and impaired reproductive cycles in *Daphnia magna* (Zhang et al., 2020b).
iii) Transfer and bioaccumulate organic pollutants to lugworms, marine amphipods, bivalves, rainbow fish, and microalgae.
iv) Increase the uptake efficiency of pollutants (Hatinoğlu and Sanin, 2021; Liu et al., 2022a).

Understanding why species interact with plastic remains a puzzle, but one factor could be its food-like resemblance. Sea turtles, for example, are drawn to plastic waste not only due to its appearance but also its odor. Over time, plastic debris accumulates algae and microorganisms in the ocean, emitting a food-like scent that attracts sea turtles in a manner similar to the actual odor of foods (Pfaller et al., 2020). Therefore, the locations where plastic debris is present in higher concentrations can work as odor uptakers and attract the attention of other species (Savoca, 2018). Also, the shape of MPs was found to control their uptake by macroinvertebrate animals (Culex sp. larvae) (Khedre et al., 2024). Shark species ingest MPs mainly through food, especially from crustaceans and mollusks, with potential risk to the reproductive cycle and immune system (Gao et al., 2023a; Orona-Návar et al., 2022). In addition, mixed toxicities of MPs with nanoparticles of CU, Ag, and Ni on microalgae and marine fish such as *Daphnia magna* were more significant than those of metals alone (Amesho et al., 2023; Hou et al., 2023). Reported studies clearly show that the amount of MPs may vary depending on the species, and impairment of food intake by aquatic organisms is the main effect found when MPs are introduced. As MPs move up the food chain, they build up in organisms, causing higher predator concentrations. This leads to biomagnification, which intensifies the presence of MPs at the trophic level. As pollutants concentrate in these trophic levels, they effectively transfer through the food chain. MPs influence the nutrition, growth, and survival of aquatic organisms and have been discovered at all levels of the food chain. The transfer of organic chemicals and metals to living organisms through the food chain can occur through various mechanisms like adsorption, aggregation, uptake, reuptake, and release of chemicals, which represent potential mechanisms for the transport of contaminants and metals (Connell, 1988; Larson, 2017). MPs are dispersed throughout the food web by ingesting smaller organisms by larger organisms that feed on them. However, the extent to which MPs impact the food chain through the transfer of chemicals is still largely unknown (Pandey et al., 2021).

Gentoo penguins were chosen as standard indicators for tracking MP particles in the Arctic marine system (Bessa et al., 2019). Analysis of penguin fecal samples from two islands revealed that 58 % of the detected MPs were microfibers, 26 % were fragments, and 16 % were films. MPs could enter penguins' digestive tracts either because penguins mistake them for food or by consuming contaminated prey and water. These MP particles accumulate in the penguins' stomachs, obstructing their eating ability and causing them to absorb pollutants from the water, which hampers their development and growth.

The Norway lobster, *Nephrops norvegicus*, inhabits European deep-sea environments, and they are strong bioindicators for MP pollution (Cau et al., 2020). These crustaceans can break down MPs into smaller particles within their stomachs, effectively acting as plastic grinders impacting lower food chain levels. In Cau et al.'s study, 85 % of the specimens examined had more MPs in their guts than in their stomachs, with lengths measuring 0.23 ± 0.16 mm and 1 ± 0.16 mm, respectively. This suggests that a significant portion of the ingested MPs is crushed by stomach mechanisms, aided by filtration systems that prevent major particles from entering the intestines. These findings highlight the emergence of a new type of secondary MPs released by lobsters into the ocean (Cau et al., 2020). Previous research has also demonstrated that persistent plastic consumption by lobsters increases mortality rates and affects their growth and reproduction (Welden and Cowie, 2016).

5. MPs as potential vectors for micropollutants

As mentioned above, MPs can absorb a variety of other environmental pollutants. These pollutants are then transported by MPs to other locations, resulting in widespread distribution of pollution (Budhiraja et al., 2022; Kurniawan et al., 2023c). The transfer of pollutants from estuaries into marine waters results in alterations to the natural environment, and further analysis is necessary to better understand this composition's consequences. Several studies have shown that MPs can transport pollutants and serve as vectors for dispersing these pollutants.

Studies use thermodynamic methods to predict which chemicals are most likely to be trapped by MPs and later ingested by organisms. Plastic polymers like polyethylene can soak up hydrophobic organic chemicals (HOCs), and the processes of absorption and release depend on the material's properties and the chemicals involved (Al-Tohamy et al., 2023). Other factors include the polymer's polarity, rubber content, and degree of crystallization (Brennecke et al., 2016; El-Aswar et al., 2022). In addition, the chemical and physical properties of organic contaminants are also crucial for their adsorption on MPs. Also, the adsorption of organic contaminants to MPs varied in seawater and freshwater, which can be attributed to the effects of salinity (Velzeboer et al., 2014).

The elevated level of crystallization likely accounts for the heightened PCB adsorption observed on PE. In fact, the adsorption of PCBs onto PE plastic films dramatically surpasses that of PS and PVC. When compared to other materials, PE exhibits the highest values for uptake, diffusion, and partition coefficients (Yu et al., 2019). The ability of PVC to adsorb PCBs diminishes as the chlorination level of congeners increases, while it improves with congeners containing lower chlorination (Llorca et al., 2020). Conversely, in comparison to PS, PVC still exhibits a greater adsorption capacity for PCBs with low chlorination levels (Gao et al., 2023b). The same results were observed for plastic pellets sampled by International Pellet Watch at various locations worldwide (Arias et al., 2023). They reported varying concentrations of polycyclic aromatic hydrocarbons (PAHs), PCBs, and “DDTs” sorbed on plastics (García-Pimentel et al., 2023). They also showed variations in contamination concentrations depending on polymer type. For example, PE contained higher polybrominated diphenyl ethers (PBDEs) levels than polypropylene (PP).

On the other hand, PP contained higher levels of PCBs, DDTs, and PAHs (Islam et al., 2023). Rochman et al. (2013) reported similar results for plastic pellets (around 3 mm in diameter) used in the field under natural environmental conditions. Higher concentrations of PAHs and PCBs were sorbed on HDPE, LDPE, and PP compared to polyethylene terephthalate (PET) and PVC.

The study by Wang et al. (Wang and Wang, 2018) compared the affinity and adsorptive capacity of MPs and natural sediment. MPs show a greater affinity for PAHs (Phe) than the natural sediment. They also found that PE exhibits the highest sorption capacity for Phe among three typical MP materials, and the adsorption equilibria for PAHs (Ex. Phe) in MPs were in the order PE < PS < PVC. The large surface area of MPs could increase the availability of sorption sites, which could be another factor for the higher affinity of PAHs to MPs. PE exhibits the highest sorption capacity for Phe among three typical MPs materials, probably due to the high crystalline structure of PE (Li et al., 2018; Wang and Wang, 2018). Phe uptake on PE, PVC, and polypropylene (PP) reached equilibrium after 24 h of exposure for all plastics (Teuten et al., 2007). Bakir et al. found the same, investigating the sorption of pollutants on plastic over 360 h, except for DDT on PE, which took 48 h (Bakir et al., 2014). The sorption of three PAHs (naphthalene, phenanthrene, and pyrene) on PP and PE pellets (1–5 mm diameter) (Fotopoulou et al., 2011). Naphthalene achieved 90 % equilibrium on PP and PE in 21 and 28 days, respectively. Phenanthrene and pyrene had slower kinetics, reaching equilibrium in 49 days (pyrene) and 63 days (phenanthrene) on PP and 128 days (pyrene) and 105 days (phenanthrene) on PE. In a separate investigation, PAH sorption onto low-density (LDPE) and high-density (HDPE) PE pellets was studied for a week (Fries and Zarfl, 2012). Not all PAHs reached equilibrium within a week, indicating faster sorption on MPs (200-250 μm) compared to larger particles (1–5 mm). For some PAHs, fluorene, phenanthrene, anthracene, and fluoranthene, 90 % equilibrium was achieved in 24 h (Bakir et al., 2014). The study results showed that the spread of pollutants (here PAHs) through the MPs matrix becomes slower as the MW of pollutants increases. The study also emphasized that pollutant sorption to plastics depends on the specific polymer and pollutant.

MPs and antibiotics are two co-occurring classes of contaminants in aqueous ecosystems. Apart from their individual toxicities, the adsorption of antibiotics to MPs may lead to their long-range transport and cause combination effects. Adsorption of five antibiotics, i.e., amoxicillin (AMX), sulfadiazine (SDZ), ciprofloxacin (CIP), trimethoprim (TMP), and tetracycline (TC) on five types of MPs (PVC, PS, PE, PA, and PP) in river-water and sea-water was investigated (Li et al., 2018). The results of this study revealed that MPs present different surface properties and degrees of crystallization. Compared to other plastics, PA showed the strongest adsorption capacity for antibiotics, probably due to its porous structure and hydrogen bonding. The adsorption amounts of five antibiotics on PS, PE, PP, PA, and PVC decreased in the order of CIP > AMX > TMP > SDZ > TC. Compared to freshwater, the adsorption capacity in seawater decreased significantly, and no adsorption was observed for CIP and AMX (Li et al., 2018). Basically, it can be said that efficient assessment of the environmental toxicity of MPs must take into account their interactions with other pollutants to determine the impact of mixed toxicities more precisely.

Table 1 summarizes microorganisms' absorption capacities of MPs in

Table 1
Absorptive capabilities of some MP in fresh water and their relationship to influencing factors.

Micropollutant(s)	K$_{wo}$	MPs type	MPs size	Exposure time	Sorption capacity	K$_d$ (L.kg^{-1})	Ref
9-Nitroanthracene	9.86	PE	100–150 μm	48 h	734.35 μg.g^{-1}	34	(Zhang et al., 2020)
		PP	100–150 μm	48 h	684.41 μg.g^{-1}	17.94	
		PS	100–150 μm	48 h	687.51 μg.g^{-1}	24.81	
Benzo[*a*]pyrene (BaP)	10.86	LDPE	11–13 μm	14 days	16.87 μg.g^{-1}	N.A.	(O'Donovan et al., 2018)
Perfluorooctane sulfonic Acid (PFOS)	Not measurable				70.22 μg/g		
PCBs	Varies	PE	N.A.	128 d	0.365–0.908 μg.g^{-1}	N.A.	(Endo et al., 2013)
Triclosan	4.76	PVC-S	<1 mm	24 h	12,700 μg.g^{-1}	1.35	(Ma et al., 2019)
		PVC-L	Ca. 74 mm	24 h	8890 μg.g^{-1}	1.05	
Azoxystrobin	3.09	PE	100 μm	24 h	17.07 μg.g^{-1}	0.1278	(Hai et al., 2020)
		PS			81.02 μg.g^{-1}	9.9060	
Picoxystrobin	3.83	PE	100 μm	24 h	22.89 μg.g^{-1}	0.1294	
		PS			25.57 μg.g^{-1}	0.1628	
Pyraclostrobin	4.23	PE	100 μm	24 h	21.25 μg.g^{-1}	0.2040	
		PS			91.23 μg.g^{-1}	14.779	
Triclosan	4.76	PS	75,4 μm	24 h	430 μg.g^{-1}	0.15	(Jiang et al., 2019)
			106,9 μm		370 μg.g^{-1}	0,0.16	
			150,5 μm		310 μg.g^{-1}	0.18	
			214,6 μm		290 μg.g^{-1}	0.17	
Bisphenol A (BPA)	3.32	PVC	13,2 μm	720 min	190 μg.g^{-1}	N.A.	(Wu et al., 2019)
Bisphenol S (BPS)					150 μg.g^{-1}		
Bisphenol F (BPF)					160 μg.g^{-1}		
Bisphenol B (BPB)					220 μg.g^{-1}		
Bisphenol AF (BPAF)					240 μg.g^{-1}		
PCBs	Varies	HDPE	N.A.	12 months	0.025 μg.g^{-1}	N.A.	(Rochman et al., 2013)
PAHs	Varies				0.797 μg.g^{-1}		
PCBs	Varies	PVC			0.002 μg.g^{-1}		
PAHs	Varies				0.027 μg.g^{-1}		
PCBs	Varies	LDPE			0.034 μg.g^{-1}		
PAHs	Varies				0.722 μg.g^{-1}		
PCBs	Varies	PP			0.027 μg.g^{-1}		
PAHs	Varies				0.122 μg.g^{-1}		
PCBs	Varies	PET			0.001 μg.g^{-1}		
PAHs	Varies				0.014 μg.g^{-1}		
Progesterone-2,3,4-^{13}C$_3$	Log K$_{ow}$ 3.87	PE	1200 μm	24 h	357.1 μg.g^{-1}	N.A.	(Siri et al., 2021)
		PS	350 μm		357.1 μg.g^{-1}		
		PP	1000 μm		322.6 μg.g^{-1}		
17β-Estradiol	3.94	PVC	0.11 mm	96	40 μg.g^{-1}	N.A.	(Lu et al., 2021)
17α-Ethynylestradiol	4.15				43.99 μg.g^{-1}		

N.A.: data not provided.

freshwater and their associations with key influencing factors.

6. Technological solutions to MPs pollution

MP's pollution is a complex issue, and tackling it requires multifaceted approaches. Current technological approaches can be categorized based on their primary objective: prevention, interception, removal, or monitoring. Prevention solutions aim to reduce or eliminate plastic waste generation at the source by promoting sustainable consumption and production patterns, regulating single-use plastics, and designing recyclable products. Interception solutions aim to capture plastic waste before it enters the waterways by improving waste collection and management systems, installing stormwater filters and screens, and engaging communities and stakeholders in clean-up activities. Removal solutions aim to recover plastic waste from water bodies using mechanical or biological methods, such as skimmers, nets, booms, bioremediation agents, or biofilters. Monitoring solutions aim to measure and track the occurrence and impacts of plastic pollution in water bodies, such as by using remote sensing technologies, citizen science initiatives, standardized protocols, and indicators (Al-Hazmi et al., 2024a; Batool et al., 2023).

Evaluation of current approaches highlights the importance of raising public awareness and implementing circular economy strategies alongside technological solutions.

Membrane filtration, with options such as microfiltration, ultrafiltration, and reverse osmosis emerging, is an effective treatment option. Ultrafiltration effectively removes MPs without additional treatment, while dynamic membranes offer accessible, low-cost cleaning advantages (Ma et al., 2019). However, membrane filtration cannot completely remove MPs and has variable efficiency based on the size of the MPs (Golgoli et al., 2021). Rapid sand filtration (RSF) works well for larger MPs, but its effectiveness is diminished for smaller MPs and often suffers from sorbent saturation and reactor hydrodynamics (Chabi et al., 2024). Membrane bioreactors (MBRs) are currently claimed to have the highest removal efficiency among currently applied technologies, with a removal rate of 99.4 % (Talvitie et al., 2017). However, implementing MBRs with all features can be expensive (Gao et al., 2022).

Adsorption methods offer another way to remove MPs, using electrostatics, hydrogen bonding, and π-π interactions. Materials such as double-layer zinc hydroxide show removal efficiency as high as 96 % in deionized water with pH dependence (Tiwari et al., 2020). Other promising sorbents include zirconium foam, chitin, and biomaterials such as biochar and magnetic biochar (Siipola et al., 2020; Wang et al., 2021; Zhuang et al., 2022). Although adsorption is a simple and effective method, it is important to consider potential secondary contamination caused by the adsorbent. Factors such as adsorbent toxicity, reusability, and biodegradability are also critical. Biochar, a natural and biodegradable material, is particularly preferred due to its minimal environmental impact (Khan Khanzada et al., 2023b; Palansooriya et al., 2022). Magnetic separation uses magnetic nanoparticles as sorbents to remove MPs. This method takes advantage of various mechanisms, including hydrophobicity, electronic interaction, and hydrogen bonding. Studies have shown removal rates exceeding 90 %, with nano-Fe$_3$O$_4$ showing average removal efficiencies between 62.83 % and 86.87 % (Shi et al., 2022). However, the widespread application of this technology still requires further development. Coagulation is a method widely used in water treatment plants to remove MPs. It involves adding coagulants to destabilize the suspended MPs and aggregate them, forming large clumps that are then separated from the water. Although the reported coagulation efficiency of <55 % of MPs in drinking water plants is relatively low, the use of multiple coagulants may improve the removal efficiency to >70 % (Zhou et al., 2021). Features such as simplicity of operation and low cost can make an affordable solution. However, some conventional coagulants can pose a toxic hazard to aquatic life (Diver et al., 2023), which makes this method a double-edged sword.

Chemical oxidation using advanced oxidation processes is another tool for MP's removal. However, the use of hydroxyl radicals generated in the photo-Fenton method and UV/H_2O_2 suffers from inadequacies in the treatment process (Vasseghian et al., 2023b). Nevertheless, techniques such as Fenton reaction and photocatalysis have been used to mineralize organic pollutants. Fenton's reagent was used to isolate MPs from organic-rich wastewater. This method has the advantage that it does not affect the chemistry or size of the microplastic and reduces exposure time from days or hours to ~10 min (Tagg et al., 2016). A Fenton system combining high pressure, hot water, and iron was developed to break down ultrahigh-molecular-weight polyethylene. The reported method efficiency was 95.9 % weight loss in 16 h and mineralization efficiency of 75.6 % in 12 h (Hu et al., 2022). However, this technology consumes much energy and requires complex reaction devices. Photocatalysis, based on hydroxyl radical generation, shows promising results for MP's oxidation. However, its effectiveness varies depending on the type of MPs, and there is concern about the toxic effect of the long-term generation of free radicals on living organisms (Xu et al., 2023). A recent review has detailed all aspects of photocatalysis as a method for treating MP waste (Hamd et al., 2022).

Biodegradation provides a more environmentally friendly and cost-effective alternative. Microorganisms and insects, including bacteria and fungi, can degrade MPs by colonizing their surfaces and secreting enzymes (Chandra and Enespa, 2020; Jabloune et al., 2020). Biodegradation offers a compelling alternative to chemical oxidation, offering a sustainable solution without relying on harmful chemicals. However, a detailed review of current approaches to MP biodegradation concluded that available knowledge about metabolic pathways and enzymes is still limited, and current methods are largely tested under laboratory conditions only (Anand et al., 2023).

While each technology has its advantages and limitations, the combination of multiple technologies holds the key to improving MP's removal efficiency in wastewater treatment plants. For example, a combination of coagulation and air flotation showed improved removal efficiency (Esfandiari and Mowla, 2021). Through a combination of electrocatalytic oxidation, advanced oxidation, and waste charcoal, the MP removal efficiency reached 99.95 % after just 90 min (Bu et al., 2022). A mixed treatment plant using a submerged MBR unit, an anaerobic tank, an aerobic tank, and a pilot-scale membrane filtration tank resulted in a removal efficiency of 99.4 % (Lares et al., 2018).

A closer look at published methods reporting high removal efficiencies shows that these methods have differential efficiency depending on the type of MPs, and no method is able to address all types of MPs with the same efficiency. Therefore, the future of MP removal lies in multifaceted treatment, prioritizing sustainable and environmentally friendly solutions.

The OceanCleanup project is a multinational initiative that receives support and recognition. It was founded in 2013 to eliminate plastic pollution in the oceans. The initiative aims to remove plastic in rivers before it reaches the sea. The system works like this: Artificial shorelines are deployed in targeted areas, consisting of a long U-shaped barrier that funnels plastic to a retention area at the other end. Plastic waste is collected, extracted, and finally recycled (Fig. 11). After numerous developments and tests, the developed system was used to clean up the Great Pacific Garbage Patch in August 2023 (Ocean Cleanup, 2023).

A similar initiative called “Plastic Fischer” was founded in 2019, and its work is currently limited to India and Indonesia (Plastic Fischer, 2023). The initiative uses a device called “TrashBoom”, a floating barrage that is stretched across a river to trap plastic waste as it flows downstream. It consists of floats made from standard plastic piping attached to wire mesh barriers that resemble fencing (Sniatala et al., 2023). The device was tested on one of Indonesia's most polluted rivers, the Citarum River, where it collected >15 tons of plastic waste in six months. However, despite the potential benefits of TrashBoom technology, it is primarily designed for mesoplastics (0.5–5 cm), macroplastics (5–50 cm), and larger plastics.

Fig. 11. Illustration of Ocean Cleanup project for plastic waste removal (Designed by the authors of the present work).

A new and simple sampling device was designed to collect MPs from the surface and subsurface layers of the water column in coastal waters of the Mediterranean Sea (Kurniawan et al., 2022). The results of the study indicate that improving waste management practices alone will not be sufficient, as it is necessary to involve the public in any efforts to mitigate the problem of plastic pollution in the region. Another point is that such simple devices need to be tested for large-scale cleanup. Low-tech, high-impact solutions to ocean plastic pollution are frequently deployed and tested by several businesses around the world to capture plastic waste from rivers before it reaches the ocean. The technologies use simple but effective devices that are easy to operate and scale in developing countries.

Instead of fighting MPs on the battlefield, the “Beat the Microbeads” campaign led by the Plastic Soup Foundation has chosen to close the city's gates to the invaders. This campaign aims to encourage companies to produce plastic-free personal care and cosmetic products (Plastic Soup Foundation, 2024). The campaign's activities, together with other efforts, led to the adoption of laws banning the use of MPs in cosmetics in several European countries and many successful stories to tell. Many European governments have passed laws banning the use of MPs in cosmetic products (European Commission, 2023).

These are just a few examples, and successful initiatives often combine multiple approaches. In this context, it is important to consider local contexts and work with various stakeholders (governments, industries, NGOs, and individuals) to find lasting solutions to curb microplastic pollution.

7. Role of legislation and policy instruments in controlling MPs pollution

Legislation and policy instruments are essential tools for preventing environmental pollution from onset. They provide the legal framework and the incentives for actors to adopt environmentally sound practices and technologies and avoid or minimize their negative impacts on the environment (Fu et al., 2022). Legislation and policy instruments can take various forms, such as regulations, standards, taxes, subsidies, permits, bans, labels, or voluntary agreements. They can target different sources and types of pollution, such as air, water, soil, noise, waste, or chemicals. They can also address different levels of governance, from local to global. The effectiveness of legislation and policy instruments depends on several factors: design, implementation, enforcement, monitoring, evaluation, and adaptation. They should be based on sound scientific evidence, stakeholder participation, public awareness, and political will. They should also be coherent and consistent with other policies and objectives, such as economic development, social equity, and human health (Fu et al., 2023). Problem statement and possible solutions are illustrated in Fig. 12.

MPs Legislation can regulate the production, use, and disposal of plastic products or monitor and report MPs pollution (Kurniawan et al., 2023b). Legislation can also encourage the development and adoption of alternatives to plastic, such as biodegradable materials, and promote public awareness and education. Moreover, legislation should be regularly reviewed and updated to reflect current knowledge and practice (Kurniawan et al., 2023c). However, the way to effective legislation is not paved and faces challenges, such as the lack of harmonized definitions and standards, the complexity and diversity of MP sources and impacts, and the need for international cooperation and coordination.

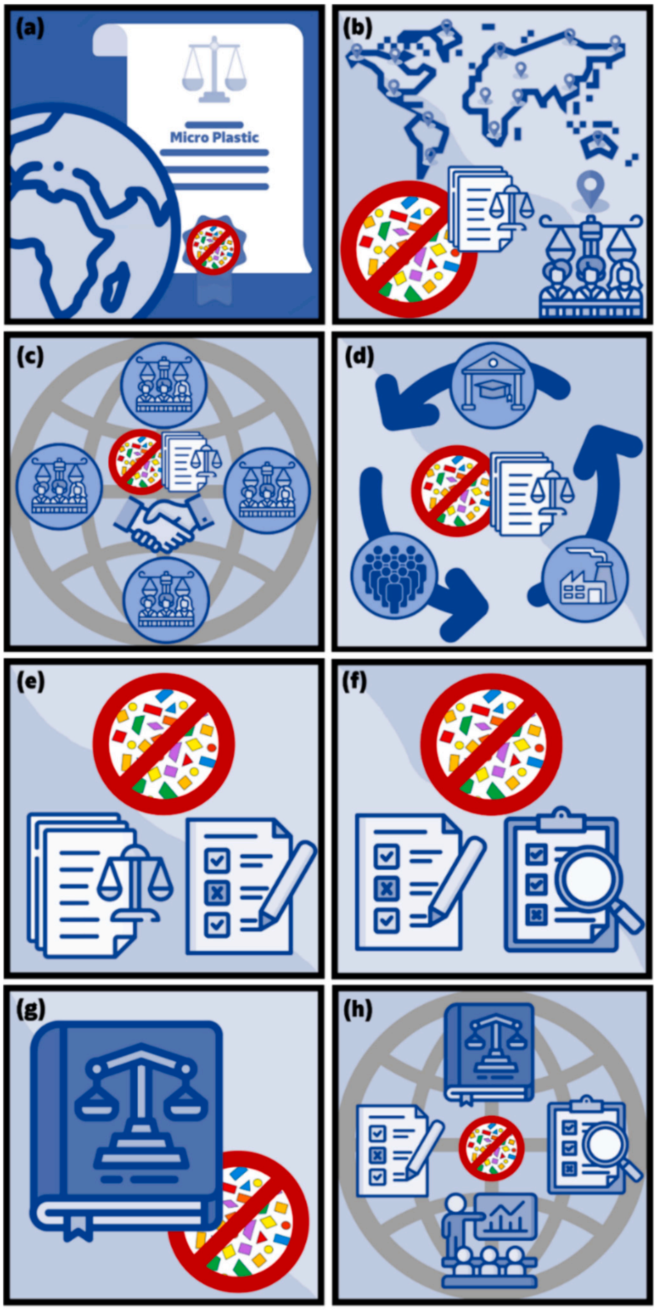


Fig. 12. The global impetus for legislation to combat MPs debris, including globalizing the regional thoughts and ideas through global communications (a), integrating the outcomes of brainstorming into instructions and commissions (b), circulating the instructions between decision-making authorities (c), signing conventions and authorizing agreements (d), establishing global legislations against MPs pollution (e), revisiting and legalizing universal legislations (f), standardizing legislation (g), and launching a blueprint for criminal industries (h) (Designed by the authors of the present work).

Policy instruments are another tool that governments can use to influence the behavior of actors in order to achieve certain policy goals. In the case of MP pollution, policy instruments can be classified into three main types: regulatory, economic, and informational. Regulatory instruments are rules or standards that impose obligations or restrictions on the production, use, or disposal of MPs. Economic instruments are incentives or disincentives that affect the costs or benefits of MPs-related activities. Informational instruments are measures that provide or disseminate knowledge or awareness about the sources, impacts, and solutions of MP pollution. Each type of instrument has its own advantages and disadvantages, depending on the policy's context and objectives (Kurniawan et al., 2023d).

Different regions have adopted various legislation and policy instruments. For example, in the European Union (EU), several directives and regulations aim to prevent, reduce, or restrict the use and release of MPs, such as the Single Use Plastics Directive (European Union, 2019), the Strategy for Plastics in a Circular Economy (The European Commission, 2018), and the European Chemical Agency's (ECHA) proposal on the restriction of intentionally added MPs (The European Chemicals Agency, 2019). These policies are based on scientific evidence and follow the precautionary principle.

One of the challenges of controlling and managing MP pollution in the environment from downstream is that it is a diffuse and transboundary problem involving multiple sources, pathways, and impacts across different sectors and regions (Liang et al., 2022). In order to prevent MP pollution in the environment from downstream, several measures need to be implemented at different levels. At the source level, the production and use of MPs should be reduced or eliminated by adopting alternative materials, improving product design, and implementing circular economy principles. At the consumer level, the awareness and behavior of individuals and households should be changed by promoting sustainable consumption patterns, reducing waste generation, and increasing recycling and reuse. At the end-of-life level, wastewater and solid waste collection and treatment should be improved by installing appropriate filters and separators, enhancing waste management infrastructure and practices, and applying the best available technologies. Environmental monitoring and remediation of MP pollution should be enhanced by developing standardized methods and indicators, conducting regular assessments and surveys, and applying effective removal and restoration techniques (Maiurova et al., 2022).

For this reason, a single policy instrument may not be sufficient and adequate to address the complexity and diversity of the issue. A more comprehensive and coordinated approach is needed, involving a mix of policy instruments that can target different aspects of the problem at different levels and scales. For example, a combination of regulatory instruments (such as bans on certain types of MPs, standards for wastewater treatment or waste management, or liability schemes for polluters) and economic instruments (such as taxes, subsidies, deposit-refund systems, or extended producer responsibility schemes) can create incentives for reducing the generation and release of MPs into the environment (Mohyuddin et al., 2022). Additionally, informational instruments (such as labeling, certification, education, or awareness campaigns) can enhance the knowledge and behavior of consumers, producers, and policymakers regarding the prevention and mitigation of MPs' pollution. Policy instruments on managing and preventing MP pollution are essential to address this complex and multifaceted issue. A summary of examples of current MP laws and regulations and their limitations is presented in Table 1.

Nevertheless, the current legal framework is fragmented and insufficient to deal with the transboundary nature and the multiple sources and impacts of MP pollution (Ulfat et al., 2023). Therefore, there is a need for a comprehensive and coherent approach that involves all relevant stakeholders and covers all stages of the plastic life cycle, from production to disposal. Possible measures include:

- The adoption of a global legally binding instrument on plastic pollution sets clear targets, standards, and obligations for the prevention, reduction, and control of MP pollution, as well as mechanisms for monitoring, reporting, and enforcement.
- Development of national strategies and action plans on MP pollution that identify the primary sources, pathways, and impacts of MP pollution in each country and establish specific measures to address them, such as bans or restrictions on certain types of MPs, incentives for the use of alternative materials, extended producer responsibility schemes, waste management improvements, public awareness campaigns, and research and innovation support.
- It enhances regional and international cooperation and coordination on MP pollution, especially among countries that share marine basins or river systems, by establishing regional agreements or frameworks, exchanging information and best practices, harmonizing standards and methods, and providing technical and financial assistance.
- It is strengthening the role and participation of non-state actors, such as industry, civil society, academia, and consumers, in developing and implementing legislation and policy on MP pollution through mechanisms such as voluntary commitments, codes of conduct, certification schemes, consumer education, and advocacy.

Concerning toxin scavengers and environmental transporters, some of the critical aspects of such legislation include:

- They defined the scope and criteria of toxin scavengers and environmental transporters, such as their sources, types, functions, applications, and potential hazards.
- It establishes the procedures and standards for evaluating, approving, and registering toxin scavengers and environmental transporters, such as their efficacy, safety, quality, and environmental impact.
- They were setting rules and guidelines for managing and supervising toxin scavengers and environmental transporters, such as their labeling, packaging, storage, transportation, handling, usage, and disposal.
- They provide the mechanisms and measures for monitoring and enforcing toxin scavengers and environmental transporters, such as inspection, testing, reporting, auditing, tracing, and sanctioning.

By implementing such legislation, the benefits of toxin scavengers and environmental transporters can be maximized while minimizing their environmental and human health risks.

8. Research gaps and future perspectives

Despite current knowledge about microplastic pollution and the extensive research conducted to track it in the environment and develop methods for eliminating it, there are still severe gaps that make our understanding of their behavior in the environment insufficient. For example, the complex interaction between MPs and environmental pollutants still requires more research to delve deeper into the behavior of MPs with other pollutants. Also, we need to investigate the behavior of MPs in simulated body fluids.

There are still many aspects of MP contamination that still require further research, such as:

- Movement of MPs through aquatic and terrestrial food webs, potentially reaching human consumption.
- Innovative technologies for the removal/remediation of MPs from various environmental media that combine both efficiency and cost-effectiveness were established.
- The development of standardized sampling and analysis methods to facilitate comparison of results and published data is made. Such methods may require international collaboration and interlaboratory efforts.
- Effects of MPs on organisms and ecosystems include the long-term ecological consequences of MPs contamination and how it may disrupt the balance of ecosystems.
- Addressing the problem of MPs and their role as vectors for micropollutants involves a multidisciplinary approach encompassing science, policy, technology, and public engagement.

Given the global nature of the plastics problem, the transition to a circular economy, where plastics are designed to be recyclable and reusable, could gain momentum. This shift will reduce the production and release of MPs into the environment. Increasing public awareness about the impacts of MPs on the environment and human health must be a priority. Educational campaigns and initiatives to promote responsible plastic use and disposal practices will become more prevalent.

CRediT authorship contribution statement

Saeed S. Albaseer: Methodology, Conceptualization. **Hussein E. Al-Hazmi:** Writing – original draft, Conceptualization. **Tonni Agustiono Kurniawan:** Writing – original draft. **Xianbao Xu:** Investigation. **Sameer A.M. Abdulrahman:** Investigation, Formal analysis. **Peyman Ezzati:** Visualization, Software. **Sajjad Habibzadeh:** Writing – review & editing. **Henner Hollert:** Writing – review & editing. **Navid Rabiee:** Writing – review & editing. **Eder C. Lima:** Writing – review & editing, Funding acquisition. **Michael Badawi:** Writing – review & editing. **Mohammad Reza Saeb:** Writing – review & editing, Visualization, Validation, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Adegoke, K.A., Adu, F.A., Oyebamiji, A.K., Bamisaye, A., Adigun, R.A., Olasoji, S.O., Ogunjinmi, O.E., 2023. Microplastics toxicity, detection, and removal from water/wastewater. Mar. Pollut. Bull. 187, 114546 https://doi.org/10.1016/j.marpolbul.2022.114546.

Agbasi, J.C., Egbueri, J.C., Pande, C.B., Khan, M.Y.A., Ighalo, J.O., Uwajingba, H.C., Abba, S.I., 2024. Review of the potential effects and remediation strategies of microplastic pollutants in drinking water sources. Anal. Lett. 0, 1–41. https://doi.org/10.1080/00032719.2024.2343366.

Ain Bhutto, S.U., You, X., 2022. Spatial distribution of microplastics in Chinese freshwater ecosystem and impacts on food webs. Environ. Pollut. 293, 118494 https://doi.org/10.1016/j.envpol.2021.118494.

Alfonso, M.B., Lindsay, D.J., Arias, A.H., Nakano, H., Jandang, S., Isobe, A., 2023. Zooplankton as a suitable tool for microplastic research. Sci. Total Environ. 905, 167329 https://doi.org/10.1016/j.scitotenv.2023.167329.

Al-Hazmi, H.E., Grubba, D., Majtacz, J., Ziembińska-Buczyńska, A., Zhai, J., Mąkinia, J., 2023a. Combined partial denitrification/anammox process for nitrogen removal in wastewater treatment. J. Environ. Chem. Eng. 11, 108978 https://doi.org/10.1016/j.jece.2022.108978.

Al-Hazmi, H.E., Lu, X., Grubba, D., Majtacz, J., Badawi, M., Mąkinia, J., 2023b. Sustainable nitrogen removal in anammox-mediated systems: microbial metabolic pathways, operational conditions and mathematical modelling. Sci. Total Environ. 868, 161633 https://doi.org/10.1016/j.scitotenv.2023.161633.

Al-Hazmi, H.E., Maktabifard, M., Grubba, D., Majtacz, J., Hassan, G.K., Lu, X., Piechota, G., Mannina, G., Bott, C.B., Mąkinia, J., 2023c. An advanced synergy of partial denitrification-anammox for optimizing nitrogen removal from wastewater: a review. Bioresour. Technol., 129168 https://doi.org/10.1016/j.biortech.2023.129168.

Al-Hazmi, H.E., Mohammadi, A., Hejna, A., Majtacz, J., Esmaeili, A., Habibzadeh, S., Saeb, M.R., Badawi, M., Lima, E.C., Mąkinia, J., 2023d. Wastewater reuse in agriculture: prospects and challenges. Environ. Res. 236, 116711 https://doi.org/10.1016/j.envres.2023.116711.

Al-Hazmi, Hussein E., Hassan, G.K., Kurniawan, T.A., Śniatała, B., Joseph, T.M., Majtacz, J., Piechota, G., Li, X., El-Gohary, F.A., Saeb, M.R., Mąkinia, J., 2024a. Technological solutions to landfill management: towards recovery of biomethane and carbon neutrality. J. Environ. Manage. 354, 120414 https://doi.org/10.1016/j.jenvman.2024.120414.

Al-Hazmi, H.E., Łuczak, J., Habibzadeh, S., Mohamed, S.H., Mohammadi, A., Esmaeili, A., Kim, S.-J., Khodadadi, Y.M., Rabiee, N., Badawi, M., Saeb, M.R., 2024b. Polysaccharide nanocomposites in wastewater treatment: a review. Chemosphere 347, 140578. https://doi.org/10.1016/j.chemosphere.2023.140578.

Al-Tohamy, R., Ali, S.S., Zhang, M., Sameh, M., Zahoor, Mahmoud, Y.A.-G., Waleed, N., Okasha, K.M., Sun, S., Sun, J., 2023. Can wood-feeding termites solve the environmental bottleneck caused by plastics? A critical state-of-the-art review. J. Environ. Manage. 326, 116606 https://doi.org/10.1016/j.jenvman.2022.116606.

Álvarez, G., Barros, Á., Velando, A., 2018. The use of European shag pellets as indicators of microplastic fibers in the marine environment. Mar. Pollut. Bull. 137, 444–448. https://doi.org/10.1016/j.marpolbul.2018.10.050.

Alvim, C., Mendoza-Roca, J.A., Bes-Piá, A., 2020. Wastewater treatment plant as microplastics release source – quantification and identification techniques. J. Environ. Manage. 255, 109739 https://doi.org/10.1016/j.jenvman.2019.109739.

Amaral-Zettler, L.A., Zettler, E.R., Mincer, T.J., Klaassen, M.A., Gallager, S.M., 2021. Biofouling impacts on polyethylene density and sinking in coastal waters: a macro/micro tipping point? Water Res. 201, 117289 https://doi.org/10.1016/j.watres.2021.117289.

Amesho, K.T.T., Chinglenthoiba, C., Samsudin, M.S.A.B., Lani, M.N., Pandey, A., Desa, M.N.M., Suresh, V., 2023. Microplastics in the environment: an urgent need for coordinated waste management policies and strategies. J. Environ. Manage. 344, 118713 https://doi.org/10.1016/j.jenvman.2023.118713.

Anand, U., Dey, S., Bontempi, E., Ducoli, S., Vethaak, A.D., Dey, A., Federici, S., 2023. Biotechnological methods to remove microplastics: a review. Environ. Chem. Lett. 21, 1787–1810. https://doi.org/10.1007/s10311-022-01552-4.

Anderson, J.C., Park, B.J., Palace, V.P., 2016. Microplastics in aquatic environments: Implications for Canadian ecosystems. Environ. Pollut. 218, 269–280. https://doi.org/10.1016/j.envpol.2016.06.074.

Arias, A.H., Alvarez, G., Pozo, K., Pribylova, P., Klanova, J., Rodríguez Pirani, L.S., Picone, A.L., Alvarez, M., Tombesi, N., 2023. Beached microplastics at the Bahia Blanca Estuary (Argentina): plastic pellets as potential vectors of environmental pollution by POPs. Mar. Pollut. Bull. 187, 114520 https://doi.org/10.1016/j.marpolbul.2022.114520.

Auta, H.S., Emenike, C.U., Fauziah, S.H., 2017. Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ. Int. 102, 165–176. https://doi.org/10.1016/j.envint.2017.02.013.

Bajt, O., 2021. From plastics to microplastics and organisms. FEBS Open Bio 11, 954–966. https://doi.org/10.1002/2211-5463.13120.

Bakir, A., Rowland, S.J., Thompson, R.C., 2012. Competitive sorption of persistent organic pollutants onto microplastics in the marine environment. Mar. Pollut. Bull. 64, 2782–2789. https://doi.org/10.1016/j.marpolbul.2012.09.010.

Bakir, A., Rowland, S.J., Thompson, R.C., 2014. Enhanced desorption of persistent organic pollutants from microplastics under simulated physiological conditions. Environ. Pollut. 185, 16–23. https://doi.org/10.1016/j.envpol.2013.10.007.

Batool, F., Kurniawan, T.A., Mohyuddin, A., Othman, M.H.D., Anouzla, A., Meidiana, C., Goh, H.H., Chew, K.W., 2023. Fixed-bed studies of landfill leachate treatment using chitosan-coated carbon composite. Water 15, 2263. https://doi.org/10.3390/w15122263.

Beiras, R., Schönemann, A.M., 2020. Currently monitored microplastics pose negligible ecological risk to the global ocean. Sci. Rep. 10, 22281. https://doi.org/10.1038/s41598-020-79304-z.

Bessa, F., Ratcliffe, N., Otero, V., Sobral, P., Marques, J.C., Waluda, C.M., Trathan, P.N., Xavier, J.C., 2019. Microplastics in gentoo penguins from the Antarctic region. Sci. Rep. 9, 14191. https://doi.org/10.1038/s41598-019-50621-2.

Botterell, Z.L.R., Lindeque, P.K., Thompson, R.C., Beaumont, N.J., 2023. An assessment of the ecosystem services of marine zooplankton and the key threats to their provision. Ecosyst. Serv. 63, 101542 https://doi.org/10.1016/j.ecoser.2023.101542.

Brennecke, D., Duarte, B., Paiva, F., Caçador, I., Canning-Clode, J., 2016. Microplastics as vector for heavy metal contamination from the marine environment. Estuar. Coast. Shelf Sci. 178, 189–195. https://doi.org/10.1016/j.ecss.2015.12.003.

Brooke, J., Micski, M., Rowland, K., 2022. Is Net Zero Enough for the Materials Production Sector? – Eunomia Research and Consulting. URL. https://eunomia.eco/reports/is-net-zero-enough-for-the-materials-production-sector/ (accessed 5.31.24).

Browne, M.A., Galloway, T., Thompson, R., 2007. Microplastic–an emerging contaminant of potential concern. Integr. Environ. Assess. Manag. 3, 559–561. https://doi.org/10.1002/ieam.5630030412.

Bu, J., Wan, Q., Deng, Z., Liu, H., Li, T., Zhou, C., Zhong, S., 2022. Waste coal cinder catalyst enhanced electrocatalytic oxidation and persulfate advanced oxidation for the degradation of sulfadiazine. Chemosphere 303, 134880. https://doi.org/10.1016/j.chemosphere.2022.134880.

Budhiraja, V., Urh, A., Horvat, P., Krzan, A., 2022. Synergistic adsorption of organic pollutants on weathered polyethylene microplastics. Polymers (Basel) 14, 2674. https://doi.org/10.3390/polym14132674.

Calero, M., Godoy, V., Quesada, L., Martín-Lara, M.Á., 2021. Green strategies for microplastics reduction. Curr. Opin. Green Sustain. Chem. 28, 100442 https://doi.org/10.1016/j.cogsc.2020.100442.

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., Uricchio, V.F., 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. Int. J. Environ. Res. Public Health 17, 1212. https://doi.org/10.3390/ijerph17041212.

Carney Almroth, B.M., Åström, L., Roslund, S., Petersson, H., Johansson, M., Persson, N.-K., 2018. Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. Environ. Sci. Pollut. Res. 25, 1191–1199. https://doi.org/10.1007/s11356-017-0528-7.

Catarci Carteny, C., Amato, E.D., Pfeiffer, F., Christia, C., Estoppey, N., Poma, G., Covaci, A., Blust, R., 2023. Accumulation and release of organic pollutants by conventional and biodegradable microplastics in the marine environment. Environ. Sci. Pollut. Res. 30, 77819–77829. https://doi.org/10.1007/s11356-023-27887-1.

Cau, A., Avio, C.G., Dessì, C., Moccia, D., Pusceddu, A., Regoli, F., Cannas, R., Follesa, M.C., 2020. Benthic crustacean digestion can modulate the environmental fate of microplastics in the deep sea. Environ. Sci. Technol. 54, 4886–4892. https://doi.org/10.1021/acs.est.9b07705.

Chabi, K., Li, J., Ye, C., Kiki, C., Xiao, X., Li, X., Guo, L., Gad, M., Feng, M., Yu, X., 2024. Rapid sand filtration for <10 μm-sized microplastic removal in tap water treatment: efficiency and adsorption mechanisms. Sci. Total Environ. 912, 169074 https://doi.org/10.1016/j.scitotenv.2023.169074.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8, 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635.

Chan, S.-P.Y., Cole, Matthew, Benny, K.K., 2020. Review: effects of microplastic on zooplankton survival and sublethal responses. In: Oceanography and Marine Biology. CRC Press.

Chandra, P., Enespa, Singh, D.P., Chowdhary, P., 2020. 22 - microplastic degradation by bacteria in aquatic ecosystem. In: Raj, A., Verma, D., Akhter, Y. (Eds.), Microorganisms for Sustainable Environment and Health. Elsevier, pp. 431–467. https://doi.org/10.1016/B978-0-12-819001-2.00022-X.

Chen, B., Dodge, M.E., Tang, W., Lu, J., Ma, Z., Fan, C.-W., Wei, S., Hao, W., Kilgore, J., Williams, N.S., Roth, M.G., Amatruda, J.F., Chen, C., Lum, L., 2009. Small molecule–mediated disruption of Wnt-dependent signaling in tissue regeneration and cancer. Nat. Chem. Biol. 5, 100–107. https://doi.org/10.1038/nchembio.137.

Chen, X., McDonald, K., Rose, M., 2023. Stemming the Plastic-Climate Crisis. In: Pacific Environment.

Chubarenko, I., Bagaev, A., Zobkov, M., Esiukova, E., 2016. On some physical and dynamical properties of microplastic particles in marine environment. Mar. Pollut. Bull. 108, 105–112. https://doi.org/10.1016/j.marpolbul.2016.04.048.

Cincinelli, A., Scopetani, C., Chelazzi, D., Martellini, T., Pogojeva, M., Slobodnik, J., 2021. Microplastics in the Black Sea sediments. Sci. Total Environ. 760, 143898 https://doi.org/10.1016/j.scitotenv.2020.143898.

Citterich, F., Lo Giudice, A., Azzaro, M., 2023. A plastic world: a review of microplastic pollution in the freshwaters of the Earth's poles. Sci. Total Environ. 869, 161847 https://doi.org/10.1016/j.scitotenv.2023.161847.

Clere, I.K., Ahmmed, F., Remoto, P.I.J.G., Fraser-Miller, S.J., Gordon, K.C., Komyakova, V., Allan, B.J.M., 2022. Quantification and characterization of microplastics in commercial fish from southern New Zealand. Mar. Pollut. Bull. 184, 114121 https://doi.org/10.1016/j.marpolbul.2022.114121.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Galloway, T.S., 2015. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod Calanus helgolandicus. Environ. Sci. Technol. 49, 1130–1137. https://doi.org/10.1021/es504525u.

Connell, D.W., 1988. Bioaccumulation behavior of persistent organic chemicals with aquatic organisms. In: Ware, G.W. (Ed.), Reviews of Environmental Contamination and Toxicology: Continuation of Residue Reviews, Reviews of Environmental Contamination and Toxicology. Springer, New York, NY, pp. 117–154. https://doi.org/10.1007/978-1-4612-3810-2_3.

Corcoran, P.L., 2015. Benthic plastic debris in marine and fresh water environments. Environ. Sci.: Processes Impacts 17, 1363–1369. https://doi.org/10.1039/C5EM00188A.

Cox, K.D., Covernton, G.A., Davies, H.L., Dower, J.F., Juanes, F., Dudas, S.E., 2019. Human consumption of microplastics. Environ. Sci. Technol. 53, 7068–7074. https://doi.org/10.1021/acs.est.9b01517.

da Costa, J.P., Duarte, A.C., Rocha-Santos, T.A.P., 2017. Microplastics–Occurrence, Fate and Behaviour in the Environment. In: Comprehensive Analytical Chemistry. Elsevier, pp. 1–24. https://doi.org/10.1016/bs.coac.2016.10.004.

da Costa, J.P., Mouneyrac, C., Costa, M., Duarte, A.C., Rocha-Santos, T., 2020. The role of legislation, regulatory initiatives and guidelines on the control of plastic pollution. Front. Environ. Sci. 8 https://doi.org/10.3389/fenvs.2020.00104.

D'Avignon, G., Gregory-Eaves, I., Ricciardi, A., 2022. Microplastics in lakes and rivers: an issue of emerging significance to limnology. Environ. Rev. 30, 228–244. https://doi.org/10.1139/er-2021-0048.

Derwis, D., Majtacz, J., Kowal, P., Al-Hazmi, H.E., Zhai, J., Ciesielski, S., Piechota, G., Mąkinia, J., 2023. Integration of the sulfate reduction and anammox processes for enhancing sustainable nitrogen removal in granular sludge reactors. Bioresour. Technol., 129264 https://doi.org/10.1016/j.biortech.2023.129264.

Díez-Minguito, M., Bermúdez, M., Gago, J., Carretero, O., Viñas, L., 2020. Observations and idealized modelling of microplastic transport in estuaries: the exemplary case of an upwelling system (Ría de Vigo, NW Spain). Mar. Chem. 222, 103780 https://doi.org/10.1016/j.marchem.2020.103780.

Ding, L., Zhang, S., Wang, X., Yang, X., Zhang, C., Qi, Y., Guo, X., 2020. The occurrence and distribution characteristics of microplastics in the agricultural soils of Shaanxi Province, in north-western China. Sci. Total Environ. 720, 137525 https://doi.org/10.1016/j.scitotenv.2020.137525.

Diver, D., Nhapi, I., Ruziwa, W.R., 2023. The potential and constraints of replacing conventional chemical coagulants with natural plant extracts in water and wastewater treatment. Environ. Adv. 13, 100421 https://doi.org/10.1016/j.envadv.2023.100421.

Dong, H., Wang, X., Niu, X., Zeng, J., Zhou, Y., Suona, Z., Yuan, Y., Chen, X., 2023. Overview of analytical methods for the determination of microplastics: current status and trends. TrAC Trends Anal. Chem. 167, 117261 https://doi.org/10.1016/j.trac.2023.117261.

El-Aswar, E.I., Ramadan, H., Elkik, H., Taha, A.G., 2022. A comprehensive review on preparation, functionalization and recent applications of nanofiber membranes in wastewater treatment. J. Environ. Manage. 301, 113908 https://doi.org/10.1016/j.jenvman.2021.113908.

Emenike, E.C., Okorie, C.J., Ojeyemi, T., Egbemhenghe, A., Iwuozor, K.O., Saliu, O.D., Okoro, H.K., Adeniyi, A.G., 2023. From oceans to dinner plates: the impact of microplastics on human health. Heliyon 9, e20440. https://doi.org/10.1016/j.heliyon.2023.e20440.

Endo, S., Yuyama, M., Takada, H., 2013. Desorption kinetics of hydrophobic organic contaminants from marine plastic pellets. Mar. Pollut. Bull. 74, 125–131. https://doi.org/10.1016/j.marpolbul.2013.07.018.

Esfandiari, A., Mowla, D., 2021. Investigation of microplastic removal from greywater by coagulation and dissolved air flotation. Process Saf. Environ. Prot. 151, 341–354. https://doi.org/10.1016/j.psep.2021.05.027.

European Commission, 2023. Measures to Restrict Microplastics [WWW Document]. European Commission. URL. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4581 (accessed 5.25.24).

European Environment Agency, 2023. Microplastics From Textiles: Towards a Circular Economy for Textiles in Europe — European Environment Agency [WWW Document]. URL. https://www.eea.europa.eu/publications/microplastics-from-textiles-towards-a (accessed 5.31.24).

European Union, 2019. Directive - 2019/904 - EN - SUP Directive - EUR-Lex [WWW Document]. URL. https://eur-lex.europa.eu/eli/dir/2019/904/oj (accessed 5.25.24).

Eze, C.G., Nwankwo, C.E., Dey, S., Sundaramurthy, S., Okeke, E.S., 2024. Food chain microplastics contamination and impact on human health: a review. Environ. Chem. Lett. https://doi.org/10.1007/s10311-024-01734-2.

Fan, J., Njuguna, J., 2016. 1 - an introduction to lightweight composite materials and their use in transport structures. In: Njuguna, J. (Ed.), Lightweight Composite Structures in Transport. Woodhead Publishing, pp. 3–34. https://doi.org/10.1016/B978-1-78242-325-6.00001-3.

FAO, 2023. The Impact of Microplastics on the Gut Microbiome and Health – A Food Safety Perspective (No. No. 21). In: Food Safety and Quality Series (Rome, Italy).

Farrell, P., Nelson, K., 2013. Trophic level transfer of microplastic: Mytilus edulis (L.) to Carcinus maenas (L.). Environ. Pollut. 177, 1–3. https://doi.org/10.1016/j.envpol.2013.01.046.

Ferrante, M.C., Monnolo, A., Del Piano, F., Mattace Raso, G., Meli, R., 2022. The pressing issue of micro- and nanoplastic contamination: profiling the reproductive alterations mediated by oxidative stress. Antioxidants 11, 193. https://doi.org/10.3390/antiox11020193.

Fotopoulou, K., Siavalas, G., Karapanagioti, H.K., Christanis, K., 2011. Phenanthrene sorption onto heterogeneous sediments containing carbonaceous materials in fresh water and in marine environments: implications for organic pollutant behavior during water mixing. In: Lambrakis, N., Stournaras, G., Katsanou, K. (Eds.), Advances in the Research of Aquatic Environment: Volume 2, Environmental Earth Sciences. Springer, Berlin, Heidelberg, pp. 211–217. https://doi.org/10.1007/978-3-642-24076-8_25.

Frère, L., Paul-Pont, I., Rinnert, E., Petton, S., Jaffré, J., Bihannic, I., Soudant, P., Lambert, C., Huvet, A., 2017. Influence of environmental and anthropogenic factors on the composition, concentration and spatial distribution of microplastics: a case study of the Bay of Brest (Brittany, France). Environ. Pollut. 225, 211–222. https://doi.org/10.1016/j.envpol.2017.03.023.

Frias, J.P.G.L., Nash, R., 2019. Microplastics: finding a consensus on the definition. Mar. Pollut. Bull. 138, 145–147. https://doi.org/10.1016/j.marpolbul.2018.11.022.

Fries, E., Zarfl, C., 2012. Sorption of polycyclic aromatic hydrocarbons (PAHs) to low and high density polyethylene (PE). Environ. Sci. Pollut. Res. Int. 19, 1296–1304. https://doi.org/10.1007/s11356-011-0655-5.

Fu, D., Kurniawan, T.A., Gui, H., Li, H., Feng, S., Li, Q., Wang, Y., 2022. Role of CuxO-anchored pyrolyzed hydrochars on H2O2-activated degradation of tetracycline: effects of pyrolysis temperature and pH. Ind. Eng. Chem. Res. 61, 8847–8857. https://doi.org/10.1021/acs.iecr.2c01100.

Fu, D., Kurniawan, T.A., Wang, Y., Zhou, Z., Wei, Q., Hu, Y., Hafiz Dzarfan Othman, M., Wayne Chew, K., Hwang Goh, H., Gui, H., 2023. Applicability of magnetic biochar derived from Fe-enriched sewage sludge for chromate removal from aqueous solution. Chem. Eng. Sci. 281, 119145 https://doi.org/10.1016/j.ces.2023.119145.

Galvão, L.S., Ferreira, R.R., Fernandes, E.M.S., Correia, C.A., Valera, T.S., dos Santos Rosa, D., Wiebeck, H., 2023. Analysis of selective fluorescence for the characterization of microplastic fibers: use of a Nile Red-based analytical method to compare between natural and synthetic fibers. J. Hazard. Mater. 443, 130217 https://doi.org/10.1016/j.jhazmat.2022.130217.

Gan, Q., Cui, J., Jin, B., 2023. Environmental microplastics: classification, sources, fates, and effects on plants. Chemosphere 313, 137559. https://doi.org/10.1016/j.chemosphere.2022.137559.

Gao, W., Zhang, Y., Mo, A., Jiang, J., Liang, Y., Cao, X., He, D., 2022. Removal of microplastics in water: technology progress and green strategies. Green Anal. Chem. 3, 100042 https://doi.org/10.1016/j.greeac.2022.100042.

Gao, Z., Chen, L., Cizdziel, J., Huang, Y., 2023a. Research progress on microplastics in wastewater treatment plants: a holistic review. J. Environ. Manage. 325, 116411 https://doi.org/10.1016/j.jenvman.2022.116411.

Gao, D., Junaid, M., Chen, X., Liao, H., Chen, G., Wang, J., 2023b. Interaction of micro(nano)plastics and bisphenols in the environment: a recent perspective on adsorption mechanisms, influencing factors and ecotoxic impacts. TrAC Trends Anal. Chem. 165, 117132 https://doi.org/10.1016/j.trac.2023.117132.

García Rellán, A., Vázquez Ares, D., Vázquez Brea, C., Francisco López, A., Bello Bugallo, P.M., 2023. Sources, sinks and transformations of plastics in our oceans: review, management strategies and modelling. Sci. Total Environ. 854, 158745 https://doi.org/10.1016/j.scitotenv.2022.158745.

García-Pimentel, M.M., Fernández, B., Campillo, J.A., Castaño-Ortiz, J.M., Gil-Solsona, R., Fernández-González, V., Muniategui-Lorenzo, S., Rodríguez-Mozaz, S., León, V.M., 2023. Floating plastics as integrative samplers of organic contaminants of legacy and emerging concern from Western Mediterranean coastal areas. Sci. Total Environ. 905, 166828 https://doi.org/10.1016/j.scitotenv.2023.166828.

Gautam, A., Gore, P.M., Kandasubramanian, B., 2020. Nanocluster materials in photosynthetic machines. Chem. Eng. J. 385, 123951 https://doi.org/10.1016/j.cej.2019.123951.

Gautam, K., Sharma, P., Dwivedi, S., Singh, A., Gaur, V.K., Varjani, S., Srivastava, J.K., Pandey, A., Chang, J.-S., Ngo, H.H., 2023. A review on control and abatement of soil pollution by heavy metals: emphasis on artificial intelligence in recovery of contaminated soil. Environ. Res. 225, 115592 https://doi.org/10.1016/j.envres.2023.115592.

Gerritse, J., Leslie, H.A., de Tender, C.A., Devriese, L.I., Vethaak, A.D., 2020. Fragmentation of plastic objects in a laboratory seawater microcosm. Sci. Rep. 10, 10945. https://doi.org/10.1038/s41598-020-67927-1.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782 https://doi.org/10.1126/sciadv.1700782.

Golgoli, M., Khiadani, M., Shafieian, A., Sen, T.K., Hartanto, Y., Johns, M.L., Zargar, M., 2021. Microplastics fouling and interaction with polymeric membranes: a review. Chemosphere 283, 131185. https://doi.org/10.1016/j.chemosphere.2021.131185.

González, M.P., Cordero-de-Castro, A., Salvatierra, D., Kholssi, R., Fernandes, M.N., Blasco, J., Araújo, C.V.M., Pereira, C.D.S., 2023. Multi-level biological responses of Daphnia magna exposed to settleable atmospheric particulate matter from metallurgical industries. Aquat. Toxicol. 263, 106692 https://doi.org/10.1016/j.aquatox.2023.106692.

Green, D.S., Colgan, T.J., Thompson, R.C., Carolan, J.C., 2019. Exposure to microplastics reduces attachment strength and alters the haemolymph proteome of blue mussels (Mytilus edulis). Environ. Pollut. 246, 423–434. https://doi.org/10.1016/j.envpol.2018.12.017.

Gunawan, G., Effendi, H., Warsiki, E., 2021. The socio-economic effect on microplastic pollution of boiled salted fish. IOP Conf. Ser.: Earth Environ. Sci. 869, 012015 https://doi.org/10.1088/1755-1315/869/1/012015.

Guo, X., Wang, J., 2019. The chemical behaviors of microplastics in marine environment: a review. Mar. Pollut. Bull. 142, 1–14. https://doi.org/10.1016/j.marpolbul.2019.03.019.

Guo, J.-J., Huang, X.-P., Xiang, L., Wang, Y.-Z., Li, Y.-W., Li, H., Cai, Q.-Y., Mo, C.-H., Wong, M.-H., 2020. Source, migration and toxicology of microplastics in soil. Environ. Int. 137, 105263 https://doi.org/10.1016/j.envint.2019.105263.

Hai, N., Liu, X., Li, Y., Kong, F., Zhang, Y., Fang, S., 2020. Effects of Microplastics on the Adsorption and Bioavailability of Three Strobilurin Fungicides. ACS Omega 5, 30679–30686. https://doi.org/10.1021/acsomega.0c04787.

Hamd, W., Daher, E.A., Tofa, T.S., Dutta, J., 2022. Recent advances in photocatalytic removal of microplastics: mechanisms, kinetic degradation, and reactor design. Front. Mar. Sci. 9 https://doi.org/10.3389/fmars.2022.885614.

Hammer, J., Kraak, M.H.S., Parsons, J.R., 2012. Plastics in the marine environment: the dark side of a modern gift. In: Whitacre, D.M. (Ed.), Reviews of Environmental Contamination and Toxicology, Reviews of Environmental Contamination and Toxicology. Springer, New York, NY, pp. 1–44. https://doi.org/10.1007/978-1-4614-3414-6_1.

Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H., Schmidt, S.N., Mayer, P., Meibom, A., Baun, A., 2017. Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota: microplastics as contaminant vectors: exploring the processes. Integr. Environ. Assess. Manag. 13, 488–493. https://doi.org/10.1002/ieam.1904.

Hasegawa, T., Nakaoka, M., 2021. Trophic transfer of microplastics from mysids to fish greatly exceeds direct ingestion from the water column. Environ. Pollut. 273, 116468 https://doi.org/10.1016/j.envpol.2021.116468.

Hatinoğlu, M.D., Sanin, F.D., 2021. Sewage sludge as a source of microplastics in the environment: a review of occurrence and fate during sludge treatment. J. Environ. Manage. 295, 113028 https://doi.org/10.1016/j.jenvman.2021.113028.

He, J., Ma, W., Han, L., Chen, L., Xu, E.G., Xing, B., Yang, Z., 2023. Unraveling the role of natural and pyrogenic dissolved organic matter in photodegradation of biodegradable microplastics in freshwater. Carbon Res. 2, 18. https://doi.org/10.1007/s44246-023-00050-8.

Horton, A.A., Jürgens, M.D., Lahive, E., van Bodegom, P.M., Vijver, M.G., 2018. The influence of exposure and physiology on microplastic ingestion by the freshwater fish Rutilus rutilus (roach) in the River Thames, UK. Environ. Pollut. 236, 188–194. https://doi.org/10.1016/j.envpol.2018.01.044.

Hossain, Md.S., 2024. People's attitudes regarding plastics and microplastics pollution: perceptions, behaviors, and policy implications. Mar. Policy 165, 106219. https://doi.org/10.1016/j.marpol.2024.106219.

Hou, L., Jin, X., Liu, N., Luo, Y., Liao, J., Guo, C., Xu, J., 2023. Effects of triadimefon fungicide on Daphnia magna: multigenerational effect and population-level ecological risk. J. Environ. Manage. 339, 117822 https://doi.org/10.1016/j.jenvman.2023.117822.

Hu, K., Zhou, P., Yang, Y., Hall, T., Nie, G., Yao, Y., Duan, X., Wang, S., 2022. Degradation of microplastics by a thermal Fenton reaction. ACS EST Eng. 2, 110–120. https://doi.org/10.1021/acsestengg.1c00323.

Hung, K.-C., Chen, Y.-L., Wu, J.-H., 2012. Natural weathering properties of acetylated bamboo plastic composites. Polym. Degrad. Stab. 97, 1680–1685. https://doi.org/10.1016/j.polymdegradstab. 2012.06.016.

Hunt, C.F., Lin, W.H., Voulvoulis, N., 2021. Evaluating alternatives to plastic microbeads in cosmetics. Nat. Sustain. 4, 366–372. https://doi.org/10.1038/s41893-020-00651-w.

Islam, M.S., Hasan, Md.R., Islam, Z., 2023. Abundance, characteristics, and spatial–temporal distribution of microplastics in sea salts along the Cox's Bazar coastal area, Bangladesh. Environ. Sci. Pollut. Res. 30, 19994–20005. https://doi.org/10.1007/s11356-022-23596-3.

Issac, M.N., Kandasubramanian, B., 2021. Effect of microplastics in water and aquatic systems. Environ. Sci. Pollut. Res. 28, 19544–19562. https://doi.org/10.1007/s11356-021-13184-2.

Jabloune, R., Khalil, M., Ben Moussa, I.E., Simao-Beaunoir, A.-M., Lerat, S., Brzezinski, R., Beaulieu, C., 2020. Enzymatic degradation of p-nitrophenyl esters, polyethylene terephthalate, cutin, and suberin by Sub1, a suberinase encoded by the plant pathogen Streptomyces scabies. Microbes Environ. 35 https://doi.org/10.1264/jsme2.ME19086.

Jamieson, A.J., Brooks, L.S.R., Reid, W.D.K., Piertney, S.B., Narayanaswamy, B.E., Linley, T.D., 2019. Microplastics and synthetic particles ingested by deep-sea amphipods in six of the deepest marine ecosystems on Earth. R. Soc. Open Sci. 6, 180667 https://doi.org/10.1098/rsos.180667.

Jiang, Y., Zhao, H., Xia, W., Li, Y., Liu, H., Hao, K., Chen, J., Sun, X., Liu, W., Li, J., Peng, Y., Hu, C., Li, C., Zhang, B., Lu, S., Cai, Z., Xu, S., 2019. Prenatal exposure to benzophenones, parabens and triclosan and neurocognitive development at 2 years. Environ. Int. 126, 413–421. https://doi.org/10.1016/j.envint.2019.01.023.

Joo, S.H., Liang, Y., Kim, M., Byun, J., Choi, H., 2021. Microplastics with adsorbed contaminants: mechanisms and treatment. Environ. Challenges 3, 100042. https://doi.org/10.1016/j.envc.2021.100042.

Kadac-Czapska, K., Knez, E., Grembecka, M., 2024. Food and human safety: the impact of microplastics. Crit. Rev. Food Sci. Nutr. 64, 3502–3521. https://doi.org/10.1080/10408398.2022.2132212.

Kane, I.A., Clare, M.A., 2019. Dispersion, accumulation, and the ultimate fate of microplastics in deep-marine environments: a review and future directions. Front. Earth Sci. 7 https://doi.org/10.3389/feart.2019.00080.

Karamanlioglu, M., Preziosi, R., Robson, G.D., 2017. Abiotic and biotic environmental degradation of the bioplastic polymer poly(lactic acid): a review. Polym. Degrad. Stab. 137, 122–130. https://doi.org/10.1016/j.polymdegradstab. 2017.01.009.

Keskin, T., Nalakath Abubackar, H., Arslan, K., Azbar, N., 2019. Chapter 12 - biohydrogen production from solid wastes. In: Pandey, A., Mohan, S.V., Chang, J.-S., Hallenbeck, P.C., Larroche, C. (Eds.), Biohydrogen, Second edition, Biomass, Biofuels, Biochemicals. Elsevier, pp. 321–346. https://doi.org/10.1016/B978-0-444-64203-5.00012-5.

Khan Khanzada, A., Al-Hazmi, H.E., Śniatała, B., Muringayil Joseph, T., Majtacz, J., Abdulrahman, S.A.M., Albaseer, S.S., Kurniawan, T.A., Rahimi-Ahar, Z., Habibzadeh, S., Mąkinia, J., 2023a. Hydrochar-nanoparticle integration for arsenic removal from wastewater: challenges, possible solutions, and future horizon. Environ. Res., 117164 https://doi.org/10.1016/j.envres.2023.117164.

Khan Khanzada, A., Al-Hazmi, H.E., Śniatała, B., Muringayil Joseph, T., Majtacz, J., Abdulrahman, S.A.M., Albaseer, S.S., Kurniawan, T.A., Rahimi-Ahar, Z., Habibzadeh, S., Mąkinia, J., 2023b. Hydrochar-nanoparticle integration for arsenic removal from wastewater: challenges, possible solutions, and future horizon. Environ. Res. 238, 117164 https://doi.org/10.1016/j.envres.2023.117164.

Khan, F., Ahmed, W., Najmi, A., Younus, M., 2019. Managing plastic waste disposal by assessing consumers' recycling behavior: the case of a densely populated developing country. Environ. Sci. Pollut. Res. 26, 33054–33066. https://doi.org/10.1007/s11356-019-06411-4.

Khedre, A.M., Ramadan, S.A., Ashry, A., Alaraby, M., 2024. Interactions between microplastics and Culex sp. larvae in wastewater. Water Environ. Res. 96, e11003 https://doi.org/10.1002/wer.11003.

Kibria, G., Nugegoda, D., Haroon, A.K.Y., 2022. Microplastic pollution and contamination of seafood (including fish, sharks, mussels, oysters, shrimps and seaweeds): a global overview. In: Hashmi, M.Z. (Ed.), Microplastic Pollution: Environmental Occurrence and Treatment Technologies, Emerging Contaminants and Associated Treatment Technologies. Springer International Publishing, Cham, pp. 277–322. https://doi.org/10.1007/978-3-030-89220-3_14.

Kumar, M., Chen, H., Sarsaiya, S., Qin, S., Liu, H., Awasthi, M.K., Kumar, S., Singh, L., Zhang, Z., Bolan, N.S., Pandey, A., Varjani, S., Taherzadeh, M.J., 2021. Current research trends on micro- and nano-plastics as an emerging threat to global environment: a review. J. Hazard. Mater. 409, 124967 https://doi.org/10.1016/j.jhazmat.2020.124967.

Kuraray Europe GmbH, 2021. Elastomers [WWW Document]. URL. https://www.kuraray.eu/product-groups/elastomers (accessed 6.1.24).

Kurniawan, T.A., Maiurova, A., Kustikova, M., Bykovskaia, E., Othman, M.H.D., Goh, H.H., 2022. Accelerating sustainability transition in St. Petersburg (Russia) through digitalization-based circular economy in waste recycling industry: a strategy to promote carbon neutrality in era of Industry 4.0. J. Clean. Prod. 363, 132452 https://doi.org/10.1016/j.jclepro.2022.132452.

Kurniawan, T.A., Haider, A., Ahmad, H.M., Mohyuddin, A., Umer Aslam, H.M., Nadeem, S., Javed, M., Othman, M.H.D., Goh, H.H., Chew, K.W., 2023a. Source, occurrence, distribution, fate, and implications of microplastic pollutants in freshwater on environment: a critical review and way forward. Chemosphere 325, 138367. https://doi.org/10.1016/j.chemosphere.2023.138367.

Kurniawan, T.A., Haider, A., Ahmad, H.M., Mohyuddin, A., Umer Aslam, H.M., Nadeem, S., Javed, M., Othman, M.H.D., Goh, H.H., Chew, K.W., 2023b. Source, occurrence, distribution, fate, and implications of microplastic pollutants in freshwater on environment: a critical review and way forward. Chemosphere 325, 138367. https://doi.org/10.1016/j.chemosphere.2023.138367.

Kurniawan, T.A., Haider, A., Mohyuddin, A., Fatima, R., Salman, M., Shaheen, A., Ahmad, H.M., Al-Hazmi, H.E., Othman, M.H.D., Aziz, F., Anouzla, A., Ali, I., 2023c. Tackling microplastics pollution in global environment through integration of applied technology, policy instruments, and legislation. J. Environ. Manage. 346, 118971 https://doi.org/10.1016/j.jenvman.2023.118971.

Kurniawan, T.A., Lo, W., Othman, M.H.D., Liang, X., Goh, H.H., Chew, K.W., 2023d. Influence of Fe2O3 and bacterial biofilms on Cu(II) distribution in a simulated aqueous solution: a feasibility study to sediments in the Pearl River Estuary (PR China). J. Environ. Manage. 329, 117047 https://doi.org/10.1016/j.jenvman.2022.117047.

Kurniawan, T.A., Bandala, E.R., Othman, M.H.D., Goh, H.H., Anouzla, A., Chew, K.W., Aziz, F., Al-Hazmi, H.E., Nisa'ul Khoir, A., 2024. Implications of climate change on water quality and sanitation in climate hotspot locations: a case study in Indonesia. Water Supply, ws2024008. https://doi.org/10.2166/ws.2024.008.

Lam, C.-S., Ramanathan, S., Carbery, M., Gray, K., Vanka, K.S., Maurin, C., Bush, R., Palanisami, T., 2018. A comprehensive analysis of plastics and microplastic legislation worldwide. Water Air Soil Pollut. 229, 345. https://doi.org/10.1007/s11270-018-4002-z.

Lares, M., Ncibi, M.C., Sillanpää, Markus, Sillanpää, Mika, 2018. Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. Water Res. 133, 236–246. https://doi.org/10.1016/j.watres.2018.01.049.

Larson, R., 2017. Reaction Mechanisms in Environmental Organic Chemistry. Routledge, New York. https://doi.org/10.1201/9780203741245.

Li, W.C., Tse, H.F., Fok, L., 2016. Plastic waste in the marine environment: a review of sources, occurrence and effects. Sci. Total Environ. 566–567, 333–349. https://doi.org/10.1016/j.scitotenv.2016.05.084.

Li, J., Zhang, K., Zhang, H., 2018. Adsorption of antibiotics on microplastics. Environ. Pollut. 237, 460–467. https://doi.org/10.1016/j.envpol.2018.02.050.

Liang, X., Kurniawan, T.A., Goh, H.H., Zhang, D., Dai, W., Liu, H., Goh, K.C., Othman, M.H.D., 2022. Conversion of landfilled waste-to-electricity (WTE) for energy efficiency improvement in Shenzhen (China): a strategy to contribute to resource recovery of unused methane for generating renewable energy on-site. J. Clean. Prod. 369, 133078 https://doi.org/10.1016/j.jclepro.2022.133078.

Liu, J., Tan, C.S.Y., Yu, Z., Li, N., Abell, C., Scherman, O.A., 2017. Tough supramolecular polymer networks with extreme stretchability and fast room-temperature self-healing. Adv. Mater. 29, 1605325 https://doi.org/10.1002/adma.201605325.

Liu, P., Qian, L., Wang, H., Zhan, X., Lu, K., Gu, C., Gao, S., 2019a. New insights into aging behavior of microplastics accelerated by advanced oxidation processes. Environ. Sci. Technol. 53, 3579–3588. https://doi.org/10.1021/acs.est.9b00493.

Liu, J., Yang, Y., Ding, J., Zhu, B., Gao, W., 2019b. Microfibers: a preliminary discussion on their definition and sources. Environ. Sci. Pollut. Res. 26, 29497–29501. https://doi.org/10.1007/s11356-019-06265-w.

Liu, S., Huang, J., Zhang, W., Shi, L., Yi, K., Yu, H., Zhang, C., Li, S., Li, J., 2022a. Microplastics as a vehicle of heavy metals in aquatic environments: a review of adsorption factors, mechanisms, and biological effects. J. Environ. Manage. 302, 113995 https://doi.org/10.1016/j.jenvman.2021.113995.

Liu, J., Liu, H., He, D., Zhang, T., Qu, J., Lv, Y., Zhang, Y., 2022b. Comprehensive effects of temperature, salinity, and current velocity on the microplastic abundance in offshore area. Pol. J. Environ. Stud. 31, 1727–1736. https://doi.org/10.15244/pjoes/142389.

Llorca, M., Schirinzi, G., Martínez, M., Barceló, D., Farré, M., 2018. Adsorption of perfluoroalkyl substances on microplastics under environmental conditions. Environ. Pollut. 235, 680–691. https://doi.org/10.1016/j.envpol.2017.12.075.

Llorca, M., Ábalos, M., Vega-Herrera, A., Adrados, M.A., Abad, E., Farré, M., 2020. Adsorption and desorption behaviour of polychlorinated biphenyls onto microplastics' surfaces in water/sediment systems. Toxics 8, 59. https://doi.org/10.3390/toxics8030059.

Lu, J., Wu, Jie, Wu, Jun, Zhang, C., Luo, Y., 2021. Adsorption and Desorption of Steroid Hormones by Microplastics in Seawater. Bull. Environ. Contam. Toxicol. 107, 730–735. https://doi.org/10.1007/s00128-020-02784-2.

Lubchenco, J., Haugan, P.M., 2023. Leveraging multi-target strategies to address plastic pollution in the context of an already stressed ocean. In: Lubchenco, J., Haugan, P.M. (Eds.), The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy. Springer International Publishing, Cham, pp. 141–184. https://doi.org/10.1007/978-3-031-16277-0_5.

Luo, J., Demchuk, Z., Zhao, X., Saito, T., Tian, M., Sokolov, A.P., Cao, P.-F., 2022. Elastic vitrimers: beyond thermoplastic and thermoset elastomers. Matter 5, 1391–1422. https://doi.org/10.1016/j.matt.2022.04.007.

Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67, 94–99. https://doi.org/10.1016/j.marpolbul.2012.11.028.

Lyu, H., Lim, J.Y., Zhang, Q., Senadheera, S.S., Zhang, C., Huang, Q., Ok, Y.S., 2024. Conversion of organic solid waste into energy and functional materials using biochar catalyst: bibliometric analysis, research progress, and directions. Appl. Catal. Environ. 340, 123223 https://doi.org/10.1016/j.apcatb.2023.123223.

Ma, B., Xue, W., Hu, C., Liu, H., Qu, J., Li, L., 2019. Characteristics of microplastic removal via coagulation and ultrafiltration during drinking water treatment. Chem. Eng. J. 359, 159–167. https://doi.org/10.1016/j.cej.2018.11.155.

Maiurova, A., Kurniawan, T.A., Kustikova, M., Bykovskaia, E., Othman, M.H.D., Singh, D., Goh, H.H., 2022. Promoting digital transformation in waste collection service and waste recycling in Moscow (Russia): applying a circular economy paradigm to mitigate climate change impacts on the environment. J. Clean. Prod. 354, 131604 https://doi.org/10.1016/j.jclepro.2022.131604.

Mamun, A.A., Prasetya, T.A.E., Dewi, I.R., Ahmad, M., 2023. Microplastics in human food chains: food becoming a threat to health safety. Sci. Total Environ. 858, 159834 https://doi.org/10.1016/j.scitotenv.2022.159834.

Mateos-Cárdenas, A., O'Halloran, J., van Pelt, F.N.A.M., Jansen, M.A.K., 2020. Rapid fragmentation of microplastics by the freshwater amphipod Gammarus duebeni (Lillj.). Sci. Rep. 10, 12799. https://doi.org/10.1038/s41598-020-69635-2.

Miraj, S.S., Parveen, N., Zedan, H.S., 2021. Plastic microbeads: small yet mighty concerning. Int. J. Environ. Health Res. 31, 788–804. https://doi.org/10.1080/09603123.2019.1689233.

Mohamadi, M., 2023. Plastic types and applications. In: Hasanzadeh, R., Mojaver, P. (Eds.), Plastic Waste Treatment and Management: Gasification Processes, Engineering Materials. Springer Nature, Switzerland, Cham, pp. 1–19. https://doi.org/10.1007/978-3-031-31160-4_1.

Mohyuddin, A., Kurniawan, T.A., Khan, Z., Nadeem, S., Javed, M., Dera, A.A., Iqbal, S., Awwad, N.S., Ibrahium, H.A., Abourehab, M.A.S., Rabea, S., Elkaeed, E.B., Asghar, M.N., Saeed, S., 2022. Comparative insights into the antimicrobial, antioxidant, and nutritional potential of the Solanum nigrum complex. Processes 10, 1455. https://doi.org/10.3390/pr10081455.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112, 39–45. https://doi.org/10.1016/j.marpolbul.2016.09.025.

Obbard, R.W., 2018. Microplastics in polar regions: the role of long range transport. In: Current Opinion in Environmental Science & Health, Micro and Nanoplastics, 1, pp. 24–29. https://doi.org/10.1016/j.coesh.2017.10.004. Edited by Dr. Teresa A.P. Rocha-Santos.

Ocean Cleanup, 2023. The Ocean Cleanup project [WWW Document]. The Ocean Cleanup. URL. https://theoceancleanup.com/about/ (accessed 5.24.24).

O'Donovan, S., Mestre, N.C., Abel, S., Fonseca, T.G., Carteny, C.C., Cormier, B., Keiter, S. H., Bebianno, M.J., 2018. Ecotoxicological Effects of Chemical Contaminants Adsorbed to Microplastics in the Clam Scrobicularia plana. Front. Mar. Sci. 5 https://doi.org/10.3389/fmars.2018.00143.

Okoye, C.O., Addey, C.I., Oderinde, O., Okoro, J.O., Uwamungu, J.Y., Ikechukwu, C.K., Okeke, E.S., Ejeromedoghene, O., Odii, E.C., 2022. Toxic chemicals and persistent organic pollutants associated with micro-and nanoplastics pollution. Chem. Eng. J. Adv. 11, 100310 https://doi.org/10.1016/j.ceja.2022.100310.

Orona-Návar, C., García-Morales, R., Loge, F.J., Mahlknecht, J., Aguilar-Hernández, I., Ornelas-Soto, N., 2022. Microplastics in Latin America and the Caribbean: a review on current status and perspectives. J. Environ. Manage. 309, 114698 https://doi.org/10.1016/j.jenvman.2022.114698.

OSPAR, 2021. Feeder Report 2021 - Production and Consumption of Plastics [WWW Document]. URL. https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/other-assessments/production-and-consumption-plastics/ (accessed 5.31.24).

Palansooriya, K.N., Sang, M.K., Igalavithana, A.D., Zhang, M., Hou, D., Oleszczuk, P., Sung, J., Ok, Y.S., 2022. Biochar alters chemical and microbial properties of microplastic-contaminated soil. Environ. Res. 209, 112807 https://doi.org/10.1016/j.envres.2022.112807.

Pandey, D., Singh, A., Ramanathan, A., Kumar, M., 2021. The combined exposure of microplastics and toxic contaminants in the floodplains of north India: a review. J. Environ. Manage. 279, 111557 https://doi.org/10.1016/j.jenvman.2020.111557.

Pedersen, A.F., Gopalakrishnan, K., Boegehold, A.G., Peraino, N.J., Westrick, J.A., Kashian, D.R., 2020. Microplastic ingestion by quagga mussels, Dreissena bugensis, and its effects on physiological processes. Environ. Pollut. 260, 113964 https://doi.org/10.1016/j.envpol.2020.113964.

Peng, G., Bellerby, R., Zhang, F., Sun, X., Li, D., 2020. The ocean's ultimate trashcan: Hadal trenches as major depositories for plastic pollution. Water Res. 168, 115121 https://doi.org/10.1016/j.watres.2019.115121.

Pfaller, J.B., Goforth, K.M., Gil, M.A., Savoca, M.S., Lohmann, K.J., 2020. Odors from marine plastic debris elicit foraging behavior in sea turtles. Curr. Biol. 30, R213–R214. https://doi.org/10.1016/j.cub.2020.01.071.

Plastic Fischer, 2023. Fisching Plastic in World's Most Polluted Rivers [WWW Document]. Plastic Fischer. URL. https://plasticfischer.com/en/pages/solution (accessed 5.24.24).

Plastic Soup Foundation, 2024. Microplastics in Cosmetics and Care Products [WWW Document]. Beat the Microbead. URL. https://www.beatthemicrobead.org/about-us/ (accessed 5.24.24).

Polyexcel, 2021. Thermoset Plastic: What It Is and Where It Is Used. Polyexcel. URL. https://polyexcel.com.br/en/product-news/thermoset-plastic-what-it-is-and-where-it-is-used/ (accessed 6.1.24).

Praveena, S.M., 2024. Exploring public awareness, influencing factors and policy implications towards microplastic pollution: perspectives from Malaysia. Mar. Policy 161, 106042. https://doi.org/10.1016/j.marpol.2024.106042.

Premakumara, D.G.J., Canete, A.M.L., Nagaishi, M., Kurniawan, T.A., 2014. Policy implementation of the Republic Act (RA) No. 9003 in the Philippines: a case study of Cebu city. In: Waste Management, Waste Management on Asia, 34, pp. 971–979. https://doi.org/10.1016/j.wasman.2013.10.040.

Proto Plastics, 2019. All You Should Know About Thermoplastic Materials [WWW Document]. Proto Plastics. URL. https://protoplastics.com/about-thermoplastic-materials/ (accessed 6.1.24).

Rahman, A.M.N.A.A., Rusli, A., Abdullah, M.K., Shuib, R.K., Hamid, Z.A.A., Ku Ishak, K. M., Mohd Zaini Makhtar, M., Jaafar, M., Shafiq, M.D., 2023. A review of microplastic surface interactions in water and potential capturing methods. Water Sci. Eng. https://doi.org/10.1016/j.wse.2023.11.008.

Rainsford, P., Rylandsholm, F.G., Jakubec, M., Silk, M., Juskewitz, E., Ericson, J.U., Svendsen, J.-S., Engh, R.A., Isaksson, J., 2023. Label-free measurement of antimicrobial peptide interactions with lipid vesicles and nanodiscs using microscale thermophoresis. Sci. Rep. 13, 12619. https://doi.org/10.1038/s41598-023-39785-0.

Randwick City Council, 2022. Coastal & Marine [WWW Document]. URL. https://www.randwick.nsw.gov.au/environment-and-sustainability/what-were-doing/coastal-and-marine (accessed 5.25.24).

Rani, L., Kaur, G., Sood, P., Kaushal, J., Srivastav, A.L., 2024. Chapter 18 - remediation strategies for the removal of microplastics from the water. In: Srivastav, A.L., Grewal, A.S., Markandeya, Pham, T.D. (Eds.), Role of Green Chemistry in Ecosystem Restoration to Achieve Environmental Sustainability, Advances in Pollution Research. Elsevier, pp. 191–200. https://doi.org/10.1016/B978-0-443-15291-7.00004-3.

Reyes-Santillán, M.C., Nandini, S., Sarma, S.S.S., 2024. Combined effects of microplastics and temperature on the competition between Brachionus havanaensis and Brachionus calyciflorus (Rotifera). Hydrobiologia 851, 3199–3211. https://doi.org/10.1007/s10750-023-05410-4.

Rochman, C.M., Hoh, E., Hentschel, B.T., Kaye, S., 2013. Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: implications for plastic marine debris. Environ. Sci. Technol. 47, 1646–1654. https://doi.org/10.1021/es303700s.

Rodríguez-Torres, R., Almeda, R., Kristiansen, M., Rist, S., Winding, M.S., Nielsen, T.G., 2020. Ingestion and impact of microplastics on arctic Calanus copepods. Aquat. Toxicol. 228, 105631 https://doi.org/10.1016/j.aquatox.2020.105631.

Sallan, M.I.B.M., Al-Hazmi, H.E., Suratman, S., Alkhadher, S.A.A., Szeląg, B., Majtacz, J., Kowal, P., Kurniawan, T.A., Piechota, G., 2023. Anthropogenic trace metals in Setiu Wetland: spatial and seasonal distribution and implications for environmental health. J. Water Process Eng. 55, 104172 https://doi.org/10.1016/j.jwpe.2023.104172.

Samani, F.A., Meunier, L., 2023. Interactions of microplastics with contaminants in freshwater systems: a review of characteristics, bioaccessibility, and environmental factors affecting sorption. Environ. Sci. Health A 58, 222. https://doi.org/10.1080/10934529.2023.2177458.

Sana, A., 2024. Detection and Identification of Microplastics in Freshwater Samples and their Toxicological Impact on *Daphnia Pulex*, A Model Organism for Freshwater.

Sapkale, D., Pandit, S., 2023. Assessment of oxidative stress, neurotoxicity, genotoxicity and prey-predator interactions in freshwater snails exposed to microplastics. In: Endocrine Abstracts. Bioscientifica. https://doi.org/10.1530/endoabs.90.P127. Presented at the ECE 2023.

Savoca, M., 2018. The ecology of an olfactory trap. Science 362, 904. https://doi.org/10.1126/science.aav6873.

Sewwandi, M., Keerthanan, S., Perera, K.I., Vithanage, M., 2023. Plastic nurdles in marine environments due to accidental spillage. In: Microplastics in the Ecosphere. John Wiley & Sons, Ltd, pp. 415–432. https://doi.org/10.1002/9781119879534.ch26.

Shen, M., Song, B., Zeng, G., Zhang, Y., Huang, W., Wen, X., Tang, W., 2020. Are biodegradable plastics a promising solution to solve the global plastic pollution? Environ. Pollut. 263, 114469 https://doi.org/10.1016/j.envpol.2020.114469.

Shi, X., Zhang, X., Gao, W., Zhang, Y., He, D., 2022. Removal of microplastics from water by magnetic nano-Fe3O4. Sci. Total Environ. 802, 149838 https://doi.org/10.1016/j.scitotenv.2021.149838.

Siipola, V., Pflugmacher, S., Romar, H., Wendling, L., Koukkari, P., 2020. Low-cost biochar adsorbents for water purification including microplastics removal. Appl. Sci. 10, 788. https://doi.org/10.3390/app10030788.

Silviana, S., Khoirudin, F.S., Pratama, F.A., Harahap, R.P.A., Hasanah, A., Ruhmaningrum, Q., Khoiriyah, L., Vianova, S., Santoso, M.N.Q., Guslamari, Y.A., Salsabila, C.A., 2022. Non-microplastic microbeads from sago liquid waste with the addition of chitosan as antibacterial function: a review. TEKNIK 43, 211–221. https://doi.org/10.14710/teknik.v43i2.40855.

Siri, C., Liu, Y., Masset, T., Dudefoi, W., Oldham, D., Minghetti, M., Grandjean, D., Breider, F., 2021. Adsorption of progesterone onto microplastics and its desorption in simulated gastric and intestinal fluids. Environ. Sci. Process. Impacts 23, 1566–1577. https://doi.org/10.1039/D1EM00226K.

Sniatala, B., Kurniawan, T.A., Sobotka, D., Makinia, J., Othman, M.H.D., 2023. Macro-nutrients recovery from liquid waste as a sustainable resource for production of recovered mineral fertilizer: uncovering alternative options to sustain global food security cost-effectively. Sci. Total Environ. 856, 159283 https://doi.org/10.1016/j.scitotenv.2022.159283.

Soursou, V., Campo, J., Picó, Y., 2023. A critical review of the novel analytical methods for the determination of microplastics in sand and sediment samples. TrAC Trends Anal. Chem. 166, 117190 https://doi.org/10.1016/j.trac.2023.117190.

Spreafico, C., Russo, D., 2023. Investigating the evolution of the technologies for collecting microplastics. J. Environ. Manage. 326, 116710 https://doi.org/10.1016/j.jenvman.2022.116710.

Strungaru, S.-A., Jijie, R., Nicoara, M., Plavan, G., Faggio, C., 2019. Micro- (nano) plastics in freshwater ecosystems: abundance, toxicological impact and quantification methodology. TrAC Trends Anal. Chem. 110, 116–128. https://doi.org/10.1016/j.trac.2018.10.025.

Sun, A., Wang, W.-X., 2023. Human exposure to microplastics and its associated health risks. Environ. Health 1, 139–149. https://doi.org/10.1021/envhealth.3c00053.

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E.J., Le Goïc, N., Quillien, V., Mingant, C., Epelboin, Y., Corporeau, C., Guyomarch, J., Robbens, J., Paul-Pont, I., Soudant, P., Huvet, A., 2016. Oyster reproduction is affected by exposure to polystyrene microplastics. Proc. Natl. Acad. Sci. 113, 2430–2435. https://doi.org/10.1073/pnas.1519019113.

Tagg, A.S., Harrison, J.P., Ju-Nam, Y., Sapp, M., Bradley, E.L., Sinclair, C.J., Ojeda, J.J., 2016. Fenton's reagent for the rapid and efficient isolation of microplastics from wastewater. Chem. Commun. 53, 372–375. https://doi.org/10.1039/C6CC08798A.

Talvitie, J., Mikola, A., Koistinen, A., Setälä, O., 2017. Solutions to microplastic pollution – removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. Water Res. 123, 401–407. https://doi.org/10.1016/j.watres.2017.07.005.

ter Halle, A., Ladirat, L., Gendre, X., Goudouneche, D., Pusineri, C., Routaboul, C., Tenailleau, C., Duployer, B., Perez, E., 2016. Understanding the fragmentation pattern of marine plastic debris. Environ. Sci. Technol. 50, 5668–5675. https://doi.org/10.1021/acs.est.6b00594.

Teuten, E.L., Rowland, S.J., Galloway, T.S., Thompson, R.C., 2007. Potential for Plastics to transport hydrophobic contaminants. Environ. Sci. Technol. 41, 7759–7764. https://doi.org/10.1021/es071737s.

The European Chemicals Agency, 2019. Restriction Proposal for Intentionally Added Microplastics in the EU – Update [WWW Document]. URL. https://echa.europa.eu/de/-/restriction-proposal-for-intentionally-added-microplastics-in-the-eu-update (accessed 6.2.24.

The European commission, 2018. The European Strategy for Plastics in a Circular Economy.

Thushari, G.G.N., Senevirathna, J.D.M., 2020. Plastic pollution in the marine environment. Heliyon 6, e04709. https://doi.org/10.1016/j.heliyon.2020.e04709.

Tiwari, E., Singh, N., Khandelwal, N., Monikh, F.A., Darbha, G.K., 2020. Application of Zn/Al layered double hydroxides for the removal of nano-scale plastic debris from aqueous systems. J. Hazard. Mater. 397, 122769 https://doi.org/10.1016/j.jhazmat.2020.122769.

Tourinho, P.S., Kočí, V., Loureiro, S., van Gestel, C.A.M., 2019. Partitioning of chemical contaminants to microplastics: sorption mechanisms, environmental distribution and effects on toxicity and bioaccumulation. Environ. Pollut. 252, 1246–1256. https://doi.org/10.1016/j.envpol.2019.06.030.

Ulfat, W., Mohyuddin, A., Amjad, M., Kurniawan, T.A., Mujahid, B., Nadeem, S., Javed, M., Amjad, A., Ashraf, A.Q., Othman, M.H.D., Hassan, S., Arif, M., 2023. Reuse of buffing dust-laden tanning waste hybridized with poly-styrene for fabrication of thermal insulation materials. Sustainability 15, 1958. https://doi.org/10.3390/su15031958.

UNEP, 2015. Plastic in Cosmetics. United Nations Environment Programme (UNEP).

Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M.B., Janssen, C.R., 2015. Microplastics are taken up by mussels (Mytilus edulis) and lugworms (Arenicola marina) living in natural habitats. Environ. Pollut. 199, 10–17. https://doi.org/10.1016/j.envpol.2015.01.008.

Vasseghian, Y., Sezgin, D., Nguyen, D.C., Hoang, H.Y., Sari Yilmaz, M., 2023a. A hybrid nanocomposite based on CuFe layered double hydroxide coated graphene oxide for photocatalytic degradation of trimethoprim. Chemosphere 322, 138243. https://doi.org/10.1016/j.chemosphere.2023.138243.

Vasseghian, Y., Sezgin, D., Nguyen, D.C., Hoang, H.Y., Sari Yilmaz, M., 2023b. A hybrid nanocomposite based on CuFe layered double hydroxide coated graphene oxide for photocatalytic degradation of trimethoprim. Chemosphere 322, 138243. https://doi.org/10.1016/j.chemosphere.2023.138243.

Velzeboer, I., Kwadijk, C.J.A.F., Koelmans, A.A., 2014. Strong sorption of PCBs to nanoplastics, microplastics, carbon nanotubes, and fullerenes. Environ. Sci. Technol. 48, 4869–4876. https://doi.org/10.1021/es405721v.

Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. Microplastic particles in sediments of Lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. In: Estuarine, Coastal and Shelf Science, Pressures, Stresses, Shocks and Trends in Estuarine Ecosystems, 130, pp. 54–61. https://doi.org/10.1016/j.ecss.2013.03.022.

Viel, T., Manfra, L., Zupo, V., Libralato, G., Cocca, M., Costantini, M., 2023. Biodegradation of plastics induced by marine organisms: future perspectives for bioremediation approaches. Polymers 15, 2673. https://doi.org/10.3390/polym15122673.

Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227. https://doi.org/10.1016/j.scitotenv.2017.03.283.

Wang, W., Wang, J., 2018. Different partition of polycyclic aromatic hydrocarbon on environmental particulates in freshwater: microplastics in comparison to natural sediment. Ecotoxicol. Environ. Saf. 147, 648–655. https://doi.org/10.1016/j.ecoenv.2017.09.029.

Wang, J., Sun, C., Huang, Q.-X., Chi, Y., Yan, J.-H., 2021. Adsorption and thermal degradation of microplastics from aqueous solutions by Mg/Zn modified magnetic biochars. J. Hazard. Mater. 419, 126486 https://doi.org/10.1016/j.jhazmat.2021.126486.

Welden, N.A.C., Cowie, P.R., 2016. Long-term microplastic retention causes reduced body condition in the langoustine, Nephrops norvegicus. Environ. Pollut. 218, 895–900. https://doi.org/10.1016/j.envpol.2016.08.020.

Winiarska, E., Jutel, M., Zemelka-Wiacek, M., 2024. The potential impact of nano- and microplastics on human health: understanding human health risks. Environ. Res. 251, 118535 https://doi.org/10.1016/j.envres.2024.118535.

World Bank Open Data, 2022. GDP Per Capita (Current US$) [WWW Document]. World Bank Open Data. URL. https://data.worldbank.org (accessed 5.22.24).

Wu, P., Huang, J., Zheng, Y., Yang, Y., Zhang, Y., He, F., Chen, H., Quan, G., Yan, J., Li, T., Gao, B., 2019. Environmental occurrences, fate, and impacts of microplastics. Ecotoxicol. Environ. Saf. 184, 109612 https://doi.org/10.1016/j.ecoenv.2019.109612.

Wu, M., Yang, C., Du, C., Liu, H., 2020. Microplastics in waters and soils: occurrence, analytical methods and ecotoxicological effects. Ecotoxicol. Environ. Saf. 202, 110910 https://doi.org/10.1016/j.ecoenv.2020.110910.

Xin, X., Chen, B., Yang, M., Gao, S., Wang, H., Gu, W., Li, X., Zhang, B., 2023. A critical review on the interaction of polymer particles and co-existing contaminants: adsorption mechanism, exposure factors, effects on plankton species. J. Hazard. Mater. 445, 130463 https://doi.org/10.1016/j.jhazmat.2022.130463.

Xu, R., Cui, L., Kang, S., 2023. Countering microplastics pollution with photocatalysis: challenge and prospects. Prog. Nat. Sci.: Mater. Int. 33, 251–266. https://doi.org/10.1016/j.pnsc.2023.08.006.

Yan, Y., Yu, Y., Sima, J., Geng, C., Yang, J., 2023. Aging behavior of microplastics accelerated by mechanical fragmentation: alteration of intrinsic and extrinsic properties. Environ. Sci. Pollut. Res. Int. 30, 90993–91006. https://doi.org/10.1007/s11356-023-28736-x.

Yang, S., Zhou, M., Chen, X., Hu, L., Xu, Y., Fu, W., Li, C., 2022. A comparative review of microplastics in lake systems from different countries and regions. Chemosphere 286, 131806. https://doi.org/10.1016/j.chemosphere.2021.131806.

Yu, F., Yang, C., Zhu, Z., Bai, X., Ma, J., 2019. Adsorption behavior of organic pollutants and metals on micro/nanoplastics in the aquatic environment. Sci. Total Environ. 694, 133643 https://doi.org/10.1016/j.scitotenv.2019.133643.

Zhang, P., Huang, P., Sun, H., Ma, J., Li, B., 2020a. The structure of agricultural microplastics (PT, PU and UF) and their sorption capacities for PAHs and PHE derivates under various salinity and oxidation treatments. Environ. Pollut. 257, 113525 https://doi.org/10.1016/j.envpol.2019.113525.

Zhang, F., Wang, Z., Song, L., Fang, H., Wang, D.-G., 2020b. Aquatic toxicity of iron-oxide-doped microplastics to Chlorella pyrenoidosa and Daphnia magna. Environ. Pollut. 257, 113451 https://doi.org/10.1016/j.envpol.2019.113451.

Zhang, Jinghua, Chen, Huangbo, He, H., Cheng, X., Ma, T., Hu, J., Yang, S., Li, S., Zhang, L., 2020. Adsorption behavior and mechanism of 9-Nitroanthracene on typical microplastics in aqueous solutions. Chemosphere 245, 125628. https://doi.org/10.1016/j.chemosphere.2019.125628.

Zhang, K., Hamidian, A.H., Tubić, A., Zhang, Y., Fang, J.K.H., Wu, C., Lam, P.K.S., 2021. Understanding plastic degradation and microplastic formation in the environment: a review. Environ. Pollut. 274, 116554 https://doi.org/10.1016/j.envpol.2021.116554.

Zhang, M., Hou, J., Wu, J., Miao, L., Zeng, Y., 2023. Effects of input concentration, media particle size, and flow rate on fate of polystyrene nanoplastics in saturated porous media. Sci. Total Environ. 881, 163237 https://doi.org/10.1016/j.scitotenv.2023.163237.

Zhou, G., Wang, Q., Li, J., Li, Q., Xu, H., Ye, Q., Wang, Y., Shu, S., Zhang, J., 2021. Removal of polystyrene and polyethylene microplastics using PAC and FeCl3 coagulation: performance and mechanism. Sci. Total Environ. 752, 141837 https://doi.org/10.1016/j.scitotenv.2020.141837.

Zhu, L., Wang, H., Chen, B., Sun, X., Qu, K., Xia, B., 2019. Microplastic ingestion in deep-sea fish from the South China Sea. Sci. Total Environ. 677, 493–501. https://doi.org/10.1016/j.scitotenv.2019.04.380.

Zhuang, J., Rong, N., Wang, X., Chen, C., Xu, Z., 2022. Adsorption of small size microplastics based on cellulose nanofiber aerogel modified by quaternary ammonium salt in water. Sep. Purif. Technol. 293, 121133 https://doi.org/10.1016/j.seppur.2022.121133.

Ziani, K., Ioniță-Mîndrican, C.-B., Mititelu, M., Neacșu, S.M., Negrei, C., Moroșan, E., Drăgănescu, D., Preda, O.-T., 2023. Microplastics: a real global threat for environment and food safety: a state of the art review. Nutrients 15, 617. https://doi.org/10.3390/nu15030617.