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Review Article

Microplastics in water: Occurrence, fate and removal

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ABSTRACT

A global study on tap water samples has found that up to 83% of these contained microplastic fibres. These findings raise concerns about their potential health risks. Ingested microplastic particles have already been associated with harmful effects in animals, which raise concerns about similar outcomes in humans. Microplastics are ubiquitous in the environment, commonly found disposed in landfills and waste sites. Within indoor environments, the common sources are synthetic textiles, plastic bottles, and packaging. From the various point sources, they are globally distributed through air and water and can enter humans through various pathways. The finding of microplastics in fresh snow in the Antarctic highlights just how widely they are dispersed. The behaviour and health risks from microplastic particles are strongly influenced by their physicochemical properties, which is why their surfaces are important. Surface interactions are also important in pollutant transport via adsorption onto the microplastic particles. Our review covers the latest findings in microplastics research including the latest statistics in their abundance, their occurrence and fate in the environment, the methods of reducing microplastics exposure and their removal. We conclude by proposing future research directions into more effective remediation methods including new technologies and sustainable green remediation methods that need to be explored to achieve success in microplastics removal from waters at large scale.

1. Introduction

1.1. Microplastics definitions – Size, shape, chemistry, location

Anthropogenic waste is a serious global environmental problem (González-Pleiter et al., 2020). Of the various waste streams, plastics are emerging as a material of concern. Between 1950 and 2015, it is estimated that approximately 6.3 billion tons of plastic waste were generated on the Earth, of which 79% has been either buried or discarded (Ding et al., 2022). Furthermore, only 9% of plastic waste has even been recycled, 12% has been incinerated and 79% accumulates in the natural environment (Geyer et al., 2017).

Plastics are durable and instead of breaking down completely, they form smaller-sized debris. According to their degradation level, they can be cycled in the atmosphere and the terrestrial and the aquatic systems (Lwanga et al., 2022). When these degraded particles become smaller than 5 mm in size, they are termed microplastics (An et al., 2022). Often, the microplastics degrade further into smaller particles and when the diameter decreases to 100 nm or less, they are termed nanoplastics, although the term microplastics includes nanoplastics (Moriwaki et al., 2022; Yang et al., 2022a). In surface waters globally (the usual source of municipal drinking water), over 91% of microplastic particles present were in the range between 20 and 100 μm, 8% between 100 and 300 μm and the rest larger than 300 μm (Uurasjärvi et al., 2020).

Microplastic fragments are commonly classified to shape: foams, fibres, films and fragments (Lozano et al., 2021), with an additional two descriptors, line and pellet, also been used in the literature (Free et al., 2014) (Fig. 1). Over 64% of plastic particles in surface waters were reported as fibres, while the rest as fragments (Uurasjärvi et al., 2020). In terms of composition, in the order of decreasing abundance, polyethylene, polyester, propylene, polyamide and polyethylene terephthalate have been found to occur in drinking water (Vitali et al., 2023).

The common plastics present in the environment includes polyamide, low-density polyethylene, polyethylene terephthalate, polypropylene, polyurethane, polystyrene and polycarbonate (Bajt, 2021; Lozano et al., 2021). The monomer structures of each plastic type (Fig. 2) are central to the environmental behaviour of the plastic

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material. In particular, the presence of oxygenated moieties aids in adsorption of the plastic to other surfaces as well as interaction with other chemicals like pollutants.

Microplastic contamination is often categorised in terms of location, viz. indoor or outdoor, and urban or remote outdoor locations (Perera et al., 2022). Particle size and plastic type vary by location (Liao et al., 2021).

1.2. Literature search methodology

The first paper on microplastics appeared in 2004, with a focus on microplastics ending up in the ocean (Thompson et al., 2004). At the time of writing, the paper had been cited over 5800 times. Interest and publication on microplastics have since increased, particularly since 2013 (Fig. 3A – Scopus search). Most of these publications are revealed in searches using the keywords 'microplastics' and 'microplastics and pollution', despite nanoplastics being more abundant and reactive as well as having greater penetration in living cells (Sharma et al., 2022). In addition to the publication statistics in Fig. 3, a more specific search on Scopus was run to count the cumulative number of publications featuring all of the search terms "microplastics AND pollution AND nanoplastics" with the additional terms "persistence", "drinking water", "health", "toxicity", "chemistry" and "accumulation" from 2013 (Fig. 3B). Additionally, a search of the literature for publications with search terms relating to "plastic pollution" and "chemistry" and "persistence" and "accumulation" and "toxicity" reveals a breakdown of the literature along the types of works in Fig. 3(C).

1.3. Health risks associated with microplastics

Nanoparticles can cross cell membranes, with phagocytic degradation by the host's body. Most naturally occurring nanoparticles are biodegradable and lack toxicity (Yang et al., 2022b). Microplastics that are smaller than 10 μm are able to cross cell membranes and enter the various systems in the animal body, with the translocation efficiency of this process increasing with decreasing microplastic size (Zhu et al., 2023).

In juvenile barramundi (*Lates calcarifer*) exposed to conventional polythene and biodegradable microplastics (one piece each of 3 mm-diameter microplastic type per ~55 g of food pellet) for 21 days, both types were observed to accumulate in gastrointestinal tracts (Xie et al., 2022). While no mortality was induced, intestinal microbiome diversity did decrease significantly in those exposed to polyethylene (Xie et al., 2022). In crayfish (*Procambarus clarkii*), the accumulation of particles (3–20 μm size) polyethylene particles has been associated with toxic effects including oxidative stress responses, hemocytic encapsulation, increased mucous secretion, disrupted microbiota balance and declination of phenoloxidase activity (Zhang et al., 2022).

In mammals such as mice, microplastic exposure has been found to have a wider range of negative health outcomes. Healthy and immune-imbalanced mice that were exposed to 500 μg/L polystyrene (5 μm) microplastics were found to have triggered intestinal immune imbalance, aggravated histopathological damage of colonic mucosa in groups with imbalance in the intestinal immunity, and disturbed the microbial community in the colon and metabolism due to the accumulation of microplastics (Liu et al., 2022). Other studies which examined the effect of polystyrene microplastics in mice have found that greater accumulation tended to occur in females (ovaries) than males (testes). In addition, greater damage to both through increased oxidative stress, altered hormone levels in the serum, greater rate of sperm deformity in males, more decreases in ovary size and number of follicles in females and a reduced pregnancy rate and with fewer embryos produced were the outcomes (Wei et al., 2022). Other studies of polystyrene microplastic effects in mice have also found that the microplastics affected the ability of mice to learn and engage their memory via oxidative stress and decreased acetylcholine (Wang et al., 2022c), disrupted the haematological system and gene expression in bone marrow cells (Sun et al., 2021), and altered hepatic lipid metabolism (Wang et al., 2022b).

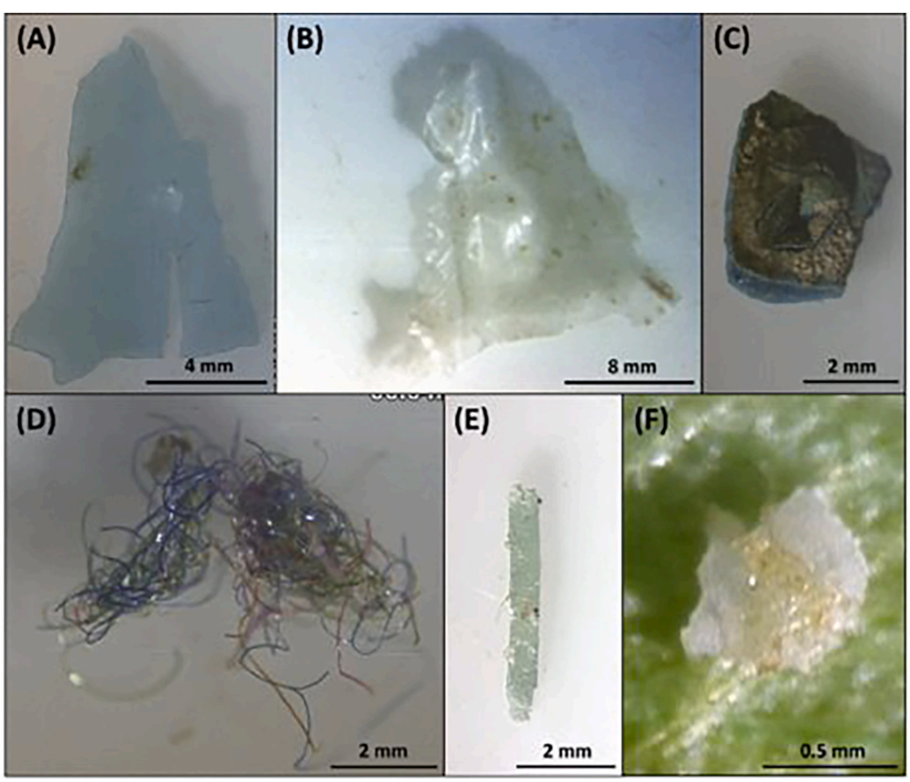

Fig. 1. The various forms of microplastics: fragment (A), film (B), foam (C), fibre (D), line (E), and (F) pellet detected in the manta trawl samples. Image reproduced with permission from Free et al. (2014).

Studies of human cadavers using micro Fourier Transform Interferometry (μFTIR) have found microplastics in the lungs (Amato-Lourenço et al., 2021), suggesting inhalation as a possible entry route (Jenner et al., 2022). It is also believed that that entry of microplastics into human cells can trigger inflammatory responses and interfere with normal physiological functioning at cellular level (Sorci and Loiseau, 2022). Moreover, when combined with other pollutants like the fungicide epoxiconazole, polystyrene microplastics have also been known to synergistically damage the intestinal barrier and liver function (Sun et al., 2022) of microplastics to humans (Zhou et al., 2023). Initial studies using rodent models do also suggest that there is likely to be oxidative stress and disruption within the individual (Thornton Hampton et al., 2022).

In the absence of data around what constitutes microplastics harm level to humans, or the effects at certain exposure levels, it is difficult to determine establish what would be 'safe levels' of exposure. Previous estimates of human consumption via plastic particles as they settle in the atmosphere during a meal alone put the figure at up to 681,000 particles/year through this avenue. Such indirect pathways of consumption complicate assessing human exposure, making it more difficult to ascertain. All exposure routes need to be mapped and determined to have a comprehensive assessment of the risk and harm.

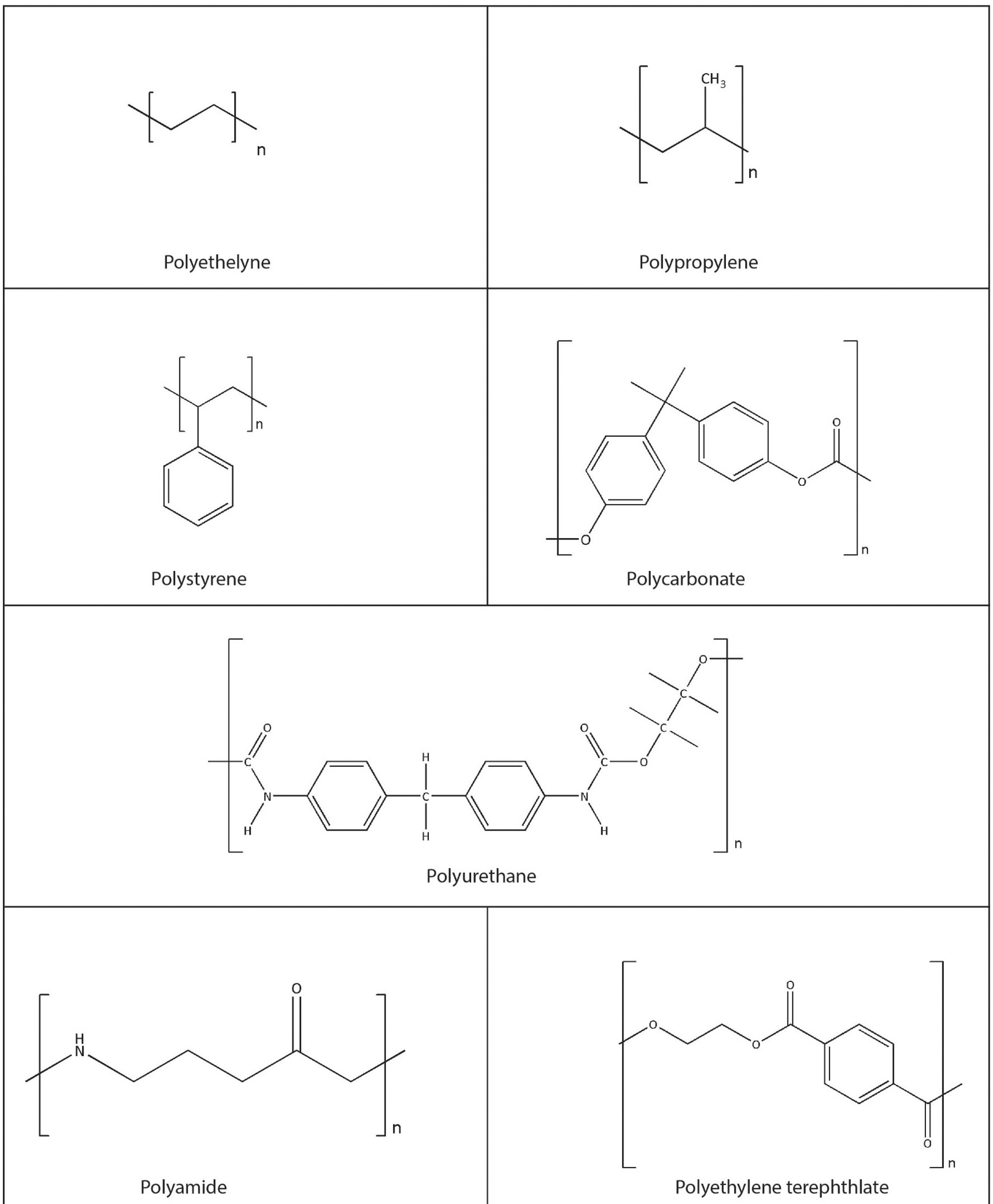

Fig. 2. Molecular structures of the monomeric units of common polymers.

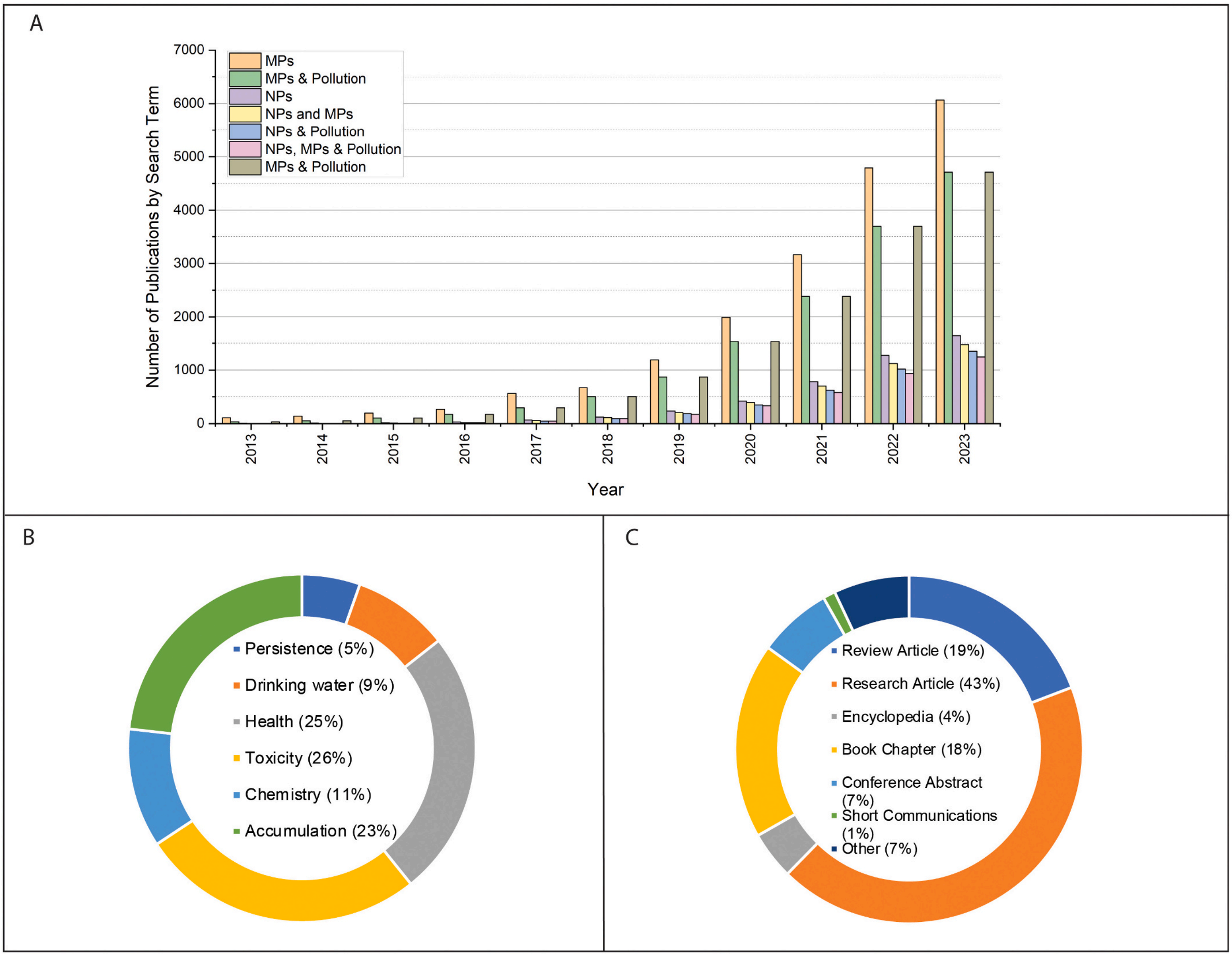

Fig. 3. Number of publications using the terms "microplastics", "nanoplastics", "nanoplastics AND microplastics" and "microplastics AND pollution" in their abstracts (A); percentage of publications based on specific terms (B) and percentage cumulative publications to date by publication type (C). Source: Scopus, searched on 20 November 2023. Abbreviations: MP, micro article, NP nano particle.

1.4. Microplastics in association with known pollutants

In both terrestrial and aquatic environments, co-occurring pollutants like organic compounds undergo the competing processes of desorption and sorption onto microplastics. This can alter the behaviour of the pollutants in the environment, including their accumulation, toxicity, transport and degradation (Wang et al., 2020a). An example is radioiodine. This isotope is a product of nuclear technology and known as a threat to human health, causing thyroid cancer (Miensah et al., 2022). In the marine environment, the isotope can adsorb to polyethylene derivatives. In this process, the physico-chemical attributes of microplastics can be altered as well (Rout et al., 2022).

The association of persistent organic pollutants (POPs) with microplastics is somewhat less clear. There was a school of thought that microplastics were not important in POPs transport. Studies comparing POPs concentrations in the liver and muscle tissue of the fulmars (seabirds) as indicator of plastic pollution differed in their findings. POPs concentrations in fulmar liver and muscle tissues were compared with ingested plastic loads in their stomachs, and it was found that rather than vector, the plastic tended to act more as a passive sampler for POPs (Herzke et al., 2016). Others also stated that despite microplastics accumulating high concentrations of POPs, they are not important for the global dispersal of POPs (Lohmann, 2017). More recently, however, studies have reported that POPs can be transported using microplastics as vectors. For example, the mobility of POPs such as phenanthrene and 4,4'-DDT onto polyvinyl chloride and onto polyethylene found that the POP/plastic combination is an important factor in the POPs transport (Bakir et al., 2014). It has been suggested that the interactions between POPs and the microplastics are controlled by several factors. The type of plastic, (polymer structure, particle size, its shape, specific area, crystallinity, and functional groups which affect polarity) influence the behaviour of the plastic. As well, the pollutant attributes (hydrophobicity which is also caused by functional groups) and environmental factors (presence of microorganisms, the salinity/ionic strength of the medium, dissolved organic matter, pH, and temperature) all play key roles (Gateuille and Naffrechoux, 2022). Changes to any of these factors would naturally be expected to disrupt the sorption kinetics, leading the POPs release and subsequent toxicity. Exogenous POPs such as polyaromatic hydrocarbons and polychlorobiphenyls tend to be adsorbed in limited amounts, hence their transport on microplastics tends to be less important than those of endogenous POPs such as phthalates and biocides which enter the plastic structure (Gateuille and Naffrechoux, 2022).

Table 1 lists some common POPs and their physicochemical properties in relation to the sorption capacity of microplastics. A key consideration in the data is the *n*-octanol/water partition coefficient

Table 1
Key physicochemical properties of common POPs in relation to the sorption capacity of microplastics.

POPs	log K_{ow}	No. of aromatic rings	Halogen group	Ionizability in environmental conditions
Polyaromatic Hydrocarbons	3.4–6.7	>2	–	No
Polychlorinated biphenyls	4.6–8.2	2	Cl	No
Polybrominated diphenyl ethers	5.7–8.3	2	Br	No
Per- & polyfluoroalkyl substances (acidic form)	2.8–7.7	0	F	Yes
Chlordecone	3.45	0	Cl	No
Heptachlor	6.1	0	Cl	No
Lindane	3.6–3.7	0	Cl	No
DDT	6.36	2	Cl	No

(K_{ow}). A high value for log K_{ow} would be associated with a greater affinity of a substance for octanol over water and in this instance, translate into a greater affinity for microplastics. From Table 1, the data shows that the notoriously toxic pesticides DDT and heptachlor have some of the greatest adsorption onto microplastic fragments among the POPs listed.

Other organic pollutants have been found to be associated with microplastics. For example, both polychlorobiphenyls (PCBs) and polybrominated diphenyl ethers have been observed in higher levels on microplastics than their corresponding zooplankton samples, raising concerns around both microplastic ingestion by marine life and chemical transfer into the food chain (Yeo et al., 2020). A study examined the kinetics of adsorption of PCBs onto four of the most common microplastic types found in the ocean (low- and high-density polyethylene, polypropylene homo- and *co*-polymer) (van der Hal et al., 2020). It found that after two weeks of exposure to and transport via microplastics ingested by the herbivorous fish, the PCBs could be identified in muscle tissues (van der Hal et al., 2020). The incidence of bioaccumulation of microplastics-transported PCBs in marine animals however has yet to be conclusively demonstrated. For instance, subjecting ten PCB congeners onto polyethylene and polystyrene microspheres did not indicate significant bioaccumulation of the chemicals in the organisms (Devriese et al., 2017).

Microplastics have also been shown to act as co-contaminants and vectors for pollutants such as heavy metals. For example, the notorious pollutant Pb(II) has been found to strongly adsorb and accumulate onto microplastics in heavy metal-contaminated aquatic environments (Chen et al., 2022b). This interaction was identified as a potential pathway for Pb(II) to enter humans and get released into the digestive system. Similarly, oral ingestion of both Cr(VI) and As(V) from microplastics has been suggested as increasing carcinogenic risks (Chen et al., 2022b).

A study of the adsorption behaviour of pharmaceutical pollutants with microplastics has found that polyethylene terephthalate, polyvinyl chloride, polyethylene, and polystyrene were carriers of amoxicillin and phenol. The equilibrium for sorption from water to plastic typically involved about 28 days for amoxicillin and about 21 days for phenol, based on the Langmuir adsorption model. Desorption correlated positively with temperature and pH (Godoy et al., 2020).

A more detailed examination organic pollutant adsorption on microplastics can be found in Costigan et al. (2022) and therefore will not be the focus of this discussion.

2. Sources and pathways of microplastics

2.1. Microplastics sources in the environment

Plastics are ubiquitous and associated with many anthropogenic activities, with use increasing with increasing population and increasing consumerism (García Rellán et al., 2023). In a study of indoor environments in China, residential apartments were found to contain the highest numbers of microplastics. Business hotels, university dormitories and classrooms and offices were next, with the predominant forms being fibres and mainly comprised of polyethylene and polypropylene (Zhu et al., 2022). Others have also reported finding mainly fibres than particles and especially the dominance of polyethylene in these particles (Amato-Lourenço et al., 2022). Studies have shown that the major sources of microplastics in indoor environments have been found as up to 60% synthetic textiles (Tian et al., 2022; Torres-Agullo et al., 2022; Xumiao et al., 2021), 30% bottles and 10% as packaging (Tian et al., 2022).

In the outdoors, origins of microplastics include plastic components in tyres and bitumen modifiers on roads (Österlund et al., 2023). At a domestic level, disposal and reusable materials like mulching films, greenhouse covers, ropes, etc. (Song et al., 2022) are also contributors. As a road material, recycled plastic as a polymer modifier in the bitumen matrix has been shown to cause earlier microplastic release into the environment than if it were added as a synthetic aggregate in the asphalt (Enfrin et al., 2022).

Polyethylene has been found to be one of the main fractions of ambient outdoor air, constituting up to 48% and 82% of microplastics found in German and Chinese cities, respectively (Mehmood and Peng, 2022). The major contributors to the release of microplastics into the air include synthetic fibres from materials like clothing, rubber erosion (e.g. from tyre wear), incineration of household waste, landfills and resuspended polymer fragments in urban dust (Amato-Lourenço et al., 2020).

Landfills and open dumps are the most common destination for plastic wastes and as a result, one of their major secondary point sources as well. Estimates place the amount of plastic waste found in municipal solid wastes to comprise of 10% of the total volume, which equates to around 300 million tons (Huang et al., 2022). Microplastics levels in leachate of up to 8.8 particles/L and 9.9 particles/L have been documented in Australia for both controlled landfill and open waste disposals, respectively (Leterme et al., 2023). In Iran, levels of up to 79 particles/L of landfill leachate has been reported (Mohammadi et al., 2022). Typically, a wide range in plastic particle counts is expected that reflects the local treatment handling practices and waste sources.

Once degraded, microplastics can remain in the soil. Lighter/smaller particles are easily transported by wind and water (Rezaei et al., 2019) thereby spreading them further than the original point sources. As a result, microplastics are now ubiquitous worldwide (Akanyange et al., 2022) and can be found throughout atmospheric, water, sediments, and within biota (Li et al., 2022b). Microplastics have even been detected in freshly fallen snow at an average content of 29 particles/L in the Antarctic (Aves et al., 2022).

Fig. 4 shows the global estimations on plastic waste per capita for the top 20 emitting nations. In Fig. 4A, the nation with the highest per capita plastic waste generation is Kuwait (at just under 700 g per person daily), while the 20th position is occupied by Vanuatu (at 300 g per person daily). In Fig. 4B, the top 20 nations which emit plastic waste into the oceans are presented. Here, the Philippines are seen to be emitting about 3.3 kg of plastic into the oceans per person per year, while Cameroon is at the 20th position with just under 0.5 kg per person annually. Interestingly, Cameroon is a largely land-locked nation in Central Africa except in the Southwest where its coastline forms part of the Gulf of Guinea (Mbevo Fendoung et al., 2022). This would suggest a greater extent of microplastics transport via existing waterbodies that empty into the Gulf. Also, in Fig. 4B, the microplastics are being emitted into the oceans in mostly Asia, the Caribbean and Africa. We also compared

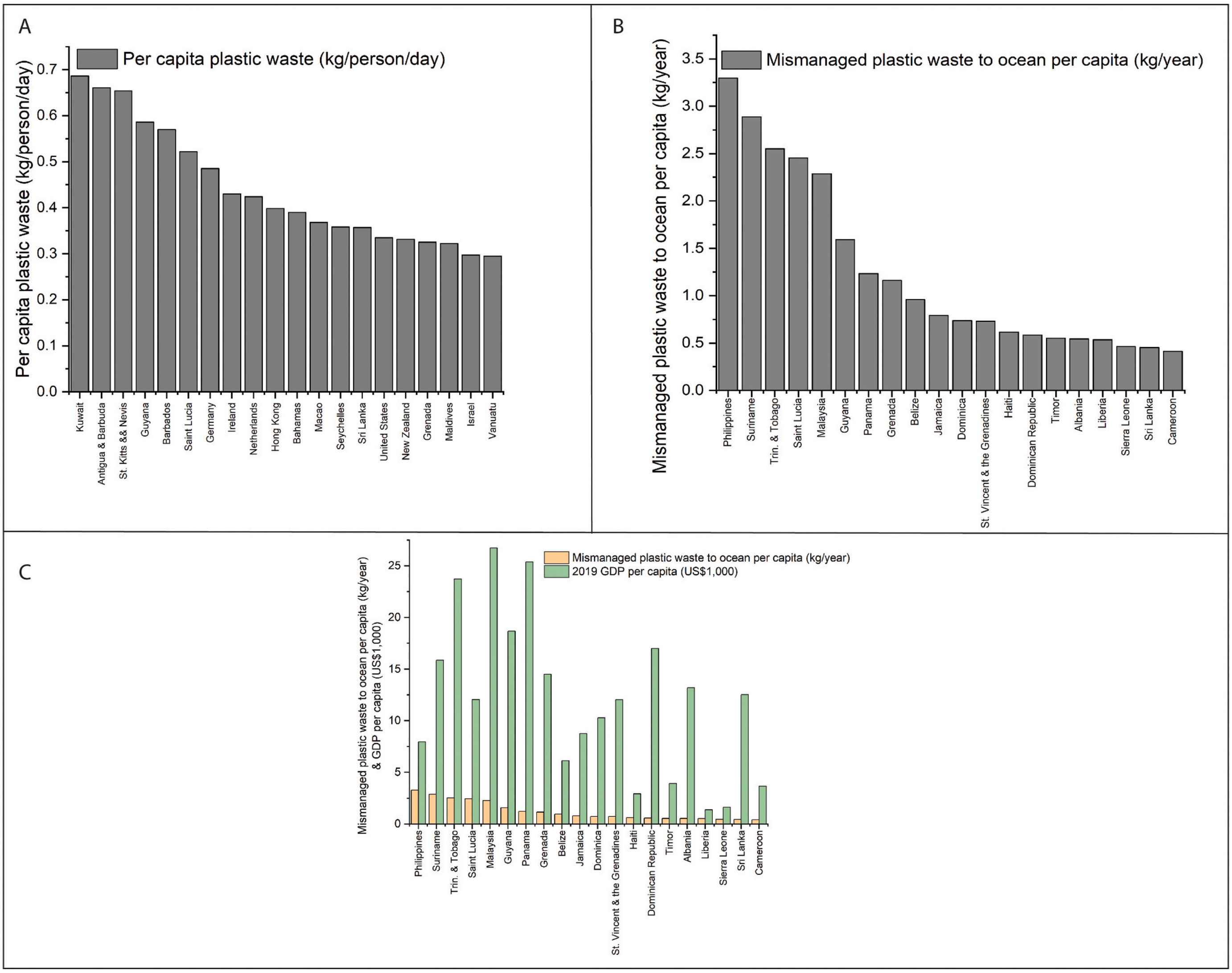

Fig. 4. Global plastic waste generation statistics depicting the 20 nations with highest amount of plastic waste (kg) per person per day (A), mismanaged plastic waste emitted into the oceans (per kg/year – B) and the inclusion of GDP per capita in green bars (C). Data sourced from Ourworldindata.org (Ritchie et al., 2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the gross domestic product (GDP) of all 20 nations listed in Fig. 4B and found no correlation between the plastic waste being emitted into the oceans and the GDP per capita. However, it is evident that there is some agglomeration of plastic waste emission into the ocean and the GDP per capita for the top 10 nations in Fig. 4B. This data would need closer examination for other associations and trends not explored in the present work.

2.2. Mobility and environmental pathways

Microplastics can be produced either as primary microplastics or as secondary degradation products of larger pieces (Lehmann et al., 2021), often from the three major terrestrial compartments: agricultural inputs, surface runoff, and the degradation of improperly disposed larger plastics (Martinho et al., 2022). However, as between 80% - 98% of microplastics in freshwater have been attributed to having land-based origins (Chen et al., 2022a; Leterme et al., 2023), these estimates may be somewhat conservative.

In aqueous environments, plastic particles made of polyvinyl chloride, nylon and polyethylene tend to sink more, while polypropylene, polyethylene and polystyrene plastic materials float or remain suspended. However, the any alteration to their density through processes like biofouling and adsorption of organic matter can lead to greater sinking behaviour, which ultimately affects their transportation (Wang et al., 2021).

Several sources of microplastics have been identified in drinking water. Water having basic pH has been demonstrated to cause the most number of microplastic particles leaching from plastic pipes compared to other parameters such as free chlorine content, pipe composition and time (Hammodat et al., 2023). In filtered water, plastic membrane filters are also contributors. During the membrane filter cleaning or if they are ageing leads to membrane rupture, causing microplastics to enter the water (Chu et al., 2022b). However, another study from Tianjin in China reported that drinking water microplastics counts decreased from 135 counts/L to 13 counts/L after water treatment (Chu et al., 2022b). Radityaningrum and co-workers examined microplastic contamination in water supply and reported that up to 84% extraction efficiency of particles sized between 1001 and 5000 μm could be achieved through water treatment (Radityaningrum et al., 2021).

Therefore, while water treatment does reduce the microplastics in water, it is unable to remove them completely. Inevitable escapee microparticles that evade water treatment due to their size or shape continue to be present in drinking water and consumed by humans. For this reason, perhaps a more robust method of microplastic removal is warranted.

Determining the volumes and major pathways of microplastics is challenging, mainly because of the varied study designs (including different sampling and analytical methods) in different studies (Schmidt et al., 2020). It is however known that aquatic dispersal is a major medium for microplastic movement, and that the density, size shape and hydrodynamic water conditions influence the movements of microplastics, in water (Zhao et al., 2020).

Mohana et al. (2022) have shown that upon ageing, microplastics can contain more surface defects such as cracking, which leads to increased surface area, and greatly exposed oxygen-bearing molecular moieties. These moieties have greater adsorption for both hydrophilic and hydrophobic microplastic molecules. Fig. 5 shows the general types of adsorption mechanisms between various organic compounds and microplastics.

The findings of others also concur with Fig. 5. For instance, drinking wmater can interact with the inner surfaces of the conduit pipes, as has been shown through batch adsorption experiments (Chu et al., 2022a). By studying the pipe scales, it was determined that van der Waals and electrostatic interactions and hydrogen bonding were the forces controlling the adsorption of polystyrene microplastics. Pore filling in scales was also the principal adsorption mechanism enabling colloidal microplastic adsorption by pipes, thus playing an essential role in the fate of colloidal MPs in drinking waters (Chu et al., 2022a).

Depending on the composition, plastics degrade differently with time and UV exposure as well as the physical environment. Fig. 6 shows scanning electron microscopic images of polyethylene terephthalate, polyamide and polyacrylonitrile ageing over a period of 10 months, in a marine environment with UV exposure.

The microplastic types in Fig. 6 differ in composition and start to crack and pit towards various stages of disintegration after 10 months. This affirms that each microplastic type is expected to weather differently compared to others, and thus, react with pollutants uniquely.

Miranda et al. (2022) have examined the sorption of pentachlorophenol on three microplastic types, low-density polyethylene, polyethylene terephthalate and unplasticized polyvinyl chloride. Among these, low density polyethylene sorption capacity increases the most after exposure to both ozone and weathering, while unplasticized polyvinyl chloride sorption capacities increase after weathering. Polyethylene terephthalate tends to be the least affected by ageing, and thus, demonstrates consistently low sorption capacity (Miranda et al., 2022).

Hydrophobic organic compounds tend to adsorb onto microplastics better than hydrophilic compounds. This property arises due to the *n*-octanol-water partition coefficient (K_{ow}) and its relationship with the dissociation constant (K_d) (Mohana et al., 2022). The greater the K_{ow} (or lesser the log K_{ow}), the greater the affinity of the molecule for a non-aqueous medium like oils and lipids. The *n*-octanol/water partition ratio or partition coefficient (log K_{ow}) and *n*-octanol/water distribution coefficient (log D) are metrics for quantifying the partitioning and thus key parameters in environmental risk assessment of chemicals via the availability and exposure and toxicity (Hodges et al., 2019). A greater K_{ow} property for hydrophobic organic compounds agrees with greater likelihood of them combining with microplastics compared to hydrophilic compounds.

2.3. Microplastics in drinking water

Ingestion is known to be the primary route of microplastics exposure to humans (Sun and Wang, 2023). Because of the regularity of drinking water consumption, humans are likely to be exposed to microplastics from drinking water (Semmouri et al., 2022).

A scientific study that analyzed tap water samples from Indonesia, India, Uganda, Ecuador, Cuba, Lebanon, United States and Europe found that 83% of these contained microplastic fibres (Kosuth et al., 2017). While the study only provided percentage of water samples to be contaminated, it did extrapolate the daily intake per human. On the basis of recommended water intake for men and women, it was predicted that consuming the affected waters would lead to men and women consuming 14 and 10 plastic particles daily (Kosuth et al., 2017). Similar studies in China estimate up to 440 microplastic particles/L of tap water (Tong et al., 2020). In Australia, a scientific study has found that bottled water contains up to 13 microplastic particles/L,

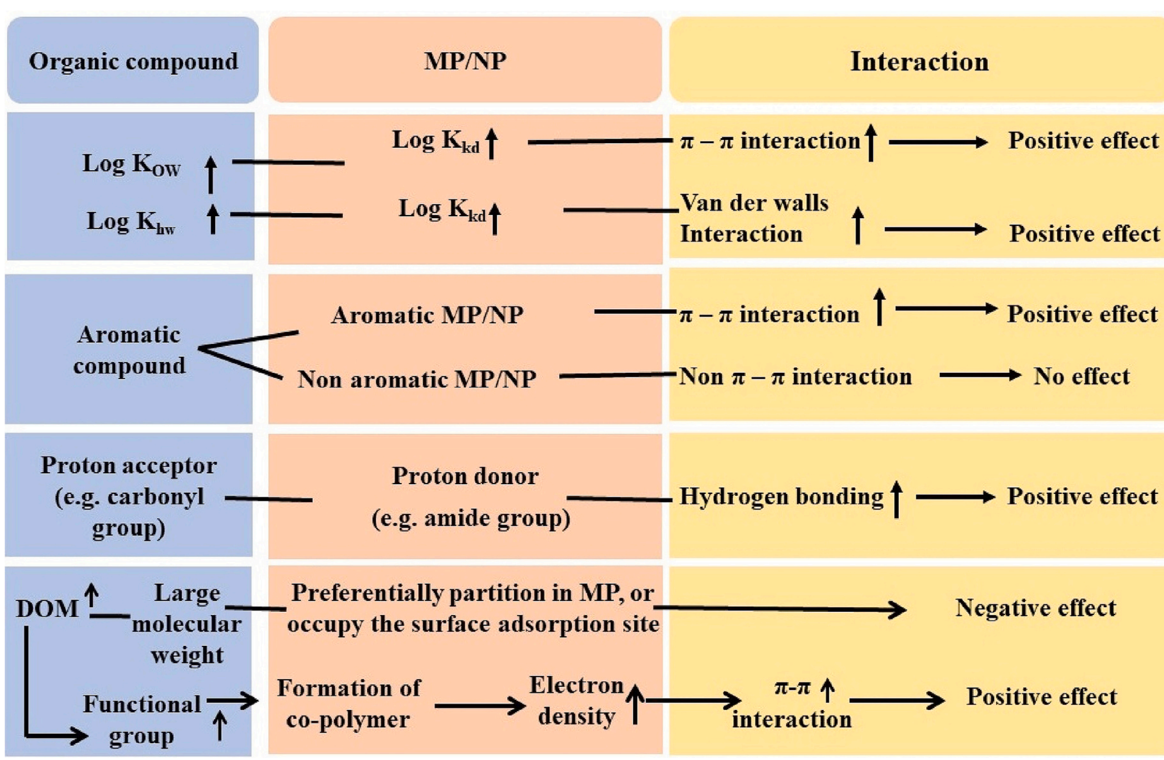

Fig. 5. Factors affecting the intermolecular interactions between organic components and nano- and microplastics. Reproduced from Mohana et al. (2022).

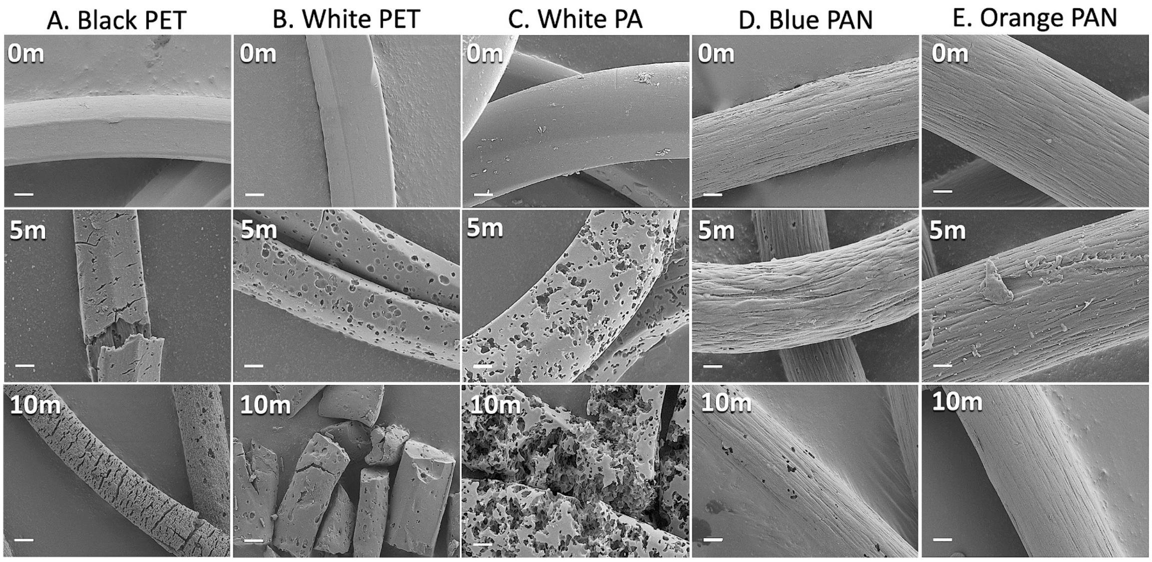

Fig. 6. SEM micrographs showing 2000× magnified time-dependent changes in surface morphology of plastics before (0 m) and after 5- (5 m) and 10-month (10 m) intervals of UV exposure in seawater. Polymer types represented are black polyethylene terephthalate (A), white polyethylene terephthalate (B), white polyamide (C), blue polyacrylonitrile (D) and orange polyacrylonitrile (E). Scale bars = 5 μm. Reproduced with permission from Sait et al. (2021) under Creative Commons CC-BY. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

predominantly in the form of polypropylene and with average size of 77 μm, putting just under a third of the population which consumes bottled water at risk of microplastics exposure (Samandra et al., 2022). In India, microplastic exposure over 24-h via drinking water has recently been estimated at 382 ± 205 particles/person. Fragments, fibres and spherical beads were the types of particles in descending order (Yadav et al., 2022). In another study of bottled drinking water in Malaysia, microplastics determined using membrane filtration were found to range from 8 to 22 particles/L, with an average of 11.7 ± 4.6 particles/L (Praveena et al., 2022). The dominant (31%) size range for the particles was from 100 to 300 μm, and the study found that packaging materials and bottle caps were the major contributors of plastic in bottled (Praveena et al., 2022). Throughout the world, drinking water is thus affected by microplastics from a variety of sources, including airborne transport.

3. Detection methods

There are several methods reported in the literature for identification and similarly, quantification of microplastics. These range from visual, spectroscopic, microscopy and chromatography-mass spectrometry.

3.1. Microscopy methods

Among these, visual observations such as those involved in optical microscopy are common mainly because of their simplicity and cost-effectiveness. They rely on particle attributes like size, shape and colour (Tran et al., 2023). However, the limitation of the optical microscopic method which requires the particles to be in the micron size range (Wang et al., 2022d) means that observing smaller particles, including nano-plastics cannot be identified. To overcome this limitation, visual observations are increasingly being combined with other methods like fluorescence often using prior staining with dyes such as Nile (Zhou et al., 2022). The dyes are able to provide fluorescent labels to the plastic particles as well as enriching microplastic polymer types and morphology (Gao et al., 2022). In particular, the solvatochromic nature of Nile reagent means that its emission spectrum shifts then the polarity of the environment it is in changes, and this is the basis of also determining whether the microplastics being examined have any polar or hydrophobic entities in the polymers (Meyers et al., 2022).

In addition to optical microscopy, scanning electron microscopy (SEM) can be used to study microplastics with much greater magnification and clearer images, allowing better distinction between microplastics and other organic compounds (Zoppas et al., 2023). Particles with sized as small as 1 nm can be identified using SEM, however it cannot distinguish colour and is often integrated with other techniques to get colour identification (Huang et al., 2023). The labour-intensive nature of manually extracting microplastics such as thin fibres for detailed examination have been overcome by other integrations of with SEM. These include, successful deep learning approaches that rely on datasets of micrographs of microplastic particles of 50 μm – 1 mm (fragments and beads) or fibres with ~10 μm diameter (Shi et al., 2022).

3.2. Spectroscopic methods

Considerable microplastics detection and identification work has been done using Raman spectroscopy. It has been applied towards the examination of microplastics in water and combined with programming language and existing Raman spectroscopic libraries for plastic has led to customized databases for identification of microplastic particles (Nesterovschi et al., 2023). Other interfaced applications of Raman spectroscopy for microplastics examination and measurement include multi-modal methods to discriminate between low and high density polyethylene particles in household items such as plastic bottles (Feng et al., 2023).

Pigments are often used in conjunction with Raman spectroscopy towards microplastics detection, and it causes overlapping signals with the Raman spectrum. One of the ways to overcome this issue is to add Fenton's reagent (Fe^{2+}, Fe^{3+}, Fe_3O_4, and $K_2Fe_4O_7$) which generate hydroxyl radical (•OH). The radicals can accelerate the degradation of the pigments before detection is made, thus eliminating the interference at the source (Liu et al., 2023b).

Fourier Transform Infrared Spectroscopy (FTIR) is also applied towards microplastics detection. Microparticles of polyethylene, polypropylene, polystyrene, polyamide and polyvinylchloride have been successfully reported to have been detected using this spectroscopic method (Rathore et al., 2023). Others have applied FTIR in various locations. For instance, mine waters have been studied at various depths for microplastics used FTIR, success in detecting between 2.5 and 20 items per litre has been reported (Brožová et al., 2023).

Like for Raman spectroscopy, integrated applications of FTIR have been published. These include, for instance Thermogravimetry-Fourier transform infrared reflection-Mass spectrometry (TG-FTIR-MS) used to track the pyrolysis of polyethylene and polyvinyl chloride microplastics in urban waters (Liu et al., 2023a). Elsewhere, attenuated Total Reflection FTIR (ATR-FTIR) has been integrated with machine Learning based methods to identify and classify microplastics using the ATR-FTIR data (Yan et al., 2022).

Presently, novel work in the microplastics counting and identification aspects have extended to submicron simultaneous infrared and Raman spectroscopies. This approach applies the complementarity of both techniques simultaneously in one instrument while preserving the submicron resolution.

3.3. Gas chromatography

Gas chromatography has been successful in identification of microplastics especially where the conventional method of counting particles fails in the case of nanoplastics (Xu et al., 2023). The use of chromatography–mass spectrometry, variously integrated can address this limitation. Pyrolysis gas-chromatography mass spectrometry has been applied to determine the mass concentrations of both microplastics and nanoplastics with different size ranges (0.01–1, 1–50, and 50–1000 μm) in wastewater treatment plants (Xu et al., 2023). This approach of pyrolysis gas chromatography mass spectrometry has also been successful in detecting microplastics in animal tissue, such as aquatic shellfish. Once the organic matter has been removed, usually by alkali digestion, organic solvents such as hexafluoroisopropanol can be used to extract polymers for subsequent analysis (Zhong et al., 2022).

Other extraction protocols such as Thermal Extraction-Desorption (TED) and thermobalances can be coupled to a gas chromatograph for identifying microplastic polymers in water (Sorolla-Rosario et al., 2023). The use of TED in this instance involves treating the solids collected from water in a furnace which negates any need for sample handling and permits smaller sample sizes. Sample handling during filter-based extractions can usually lead to losses and introduces inhomogeneity on the filter surface (Sorolla-Rosario et al., 2023).

4. Microplastic removal methods

Recent work suggests that boiling water can remove up to 80% of micro- and nano-sized plastics fragments made of polystyrene, polyethylene and polypropylene, which can co-precipitate when water containing calcium carbonate is boiled (Yu et al., 2024). However, this still excludes polyvinyl chloride which due to its chlorine presence is the most harmful of all plastic types and is a known mutagen (Colzi et al., 2022; Kudzin et al., 2023).

From an overall perspective factoring in both scale and logistics, the coagulation sedimentation process (CSP) is the most effective and economical method of removing microplastics from water because of its simplicity, speed and efficiency (Gao and Liu, 2022). Coagulation is an important step in removing microplastics as it is expected to isolate microplastics from the liquid phase (Zhang et al., 2021). However, its success is not always assured. The large variation in microplastic sizes, coagulant hydrolysate inefficiency in bridging and sweeping the particles and the low microplastic densities are some of the reasons why coagulation may fail (Zhang et al., 2021). For larger plastic particles (size >250 μm), the overall removal efficiencies of up to 90% have been reported, while the efficiency reduces to below 50% for smaller particles (< 50 μm) (Tang et al., 2023). Research into more effective remediation methods continues, including based on new technologies such as those involving nanotechnology.

Electrocoagulation has been reported as one effective technology for microplastic removal from water (Luo et al., 2022). It involves passing direct current through two sacrificial electrodes immersed into a solution. Oxidation at the sacrificial anode causes its dissolution (hence the term 'sacrificial") (Negash et al., 2023). When the anode is metallic, it combines with the hydroxide ions forming charged, hydrolysed species, which can adsorb the negatively-charged microplastic surfaces (Senathirajah et al., 2023). The electrolysis set up is relatively simple and applied potentials up to 24 V have been reported (Amri et al., 2023).

The effect of DOM in tailwater on microplastics during electrocoagulation has been studied and it has been found that in tailwater, DOM promotes the production of flocs and free radicals via electrocoagulation. Their setup was based on a direct current supply, using an iron anode and graphite cathode, over a 4-h reaction time (Luo et al., 2022). This setup was at laboratory scale and would require considerable investment to be attempted in municipal water treatment. The Fe^{2+} and Fe^{3+} which are adsorbed on the surface of DOM molecules via attachment to •OH accelerates the production of free radicals and thus promotes the ageing of microplastics. This is why electrocoagulation is preferred to removal microplastics in water with high concentration of DOM (Luo et al., 2022).

Sturm et al. (2022) have used organosilanes for microplastics agglomeration-fixation and investigated how biofilm affects this process. The biofilm was grown on the microplastics for a week. The authors reported that comparing five polymer types (polyethylene, polypropylene, polyamide, polyester, and polyvinyl chloride) and three organosilanes, the biofilm coverage caused a reduced removal efficiency for all combinations tested. The surface chemistry of the microplastics was believed to have been changed, which affected the interaction with the organosilanes (Sturm et al., 2022). Therefore, the surface chemistry is critical in ensuring successful agglomeration between plastics.

Coagulation combined with flocculation can be another approach in removing microplastics from water. The method initially involves addition of chemicals (coagulants) followed by agglomeration to form flocs. Due to their greater density, the flocs can be settled and thus removed from water and wastewater by sedimentation. Coagulation-flocculation is not a new approach – it has been used in water treatment for decreasing turbidity, and has been applied for the removal of polystyrene beads of 100 μm size and 1.04–1.06 g/cm^3 density (Li et al., 2021). Removal rates with 7-min flocculation and 30-min sedimentation time were reported to be as high as 98% in waters of pH 5.0 (Li et al., 2021). Others have combined magnesium hydroxide formed under alkaline conditions with anionic polyacrylamide as a dual coagulant to treat simulated natural water of polyethylene. The extraction efficiency was reported as 85% (Li et al., 2022a). However, the use of polyacrylamide as a synthetic chemical towards the removal of another synthetic chemical raises questions of the chemical footprint of the method, as well as reporting a lower extraction than that by Li et al. for polystyrene (Li et al., 2021). In addition, using percentage recoveries as an index of efficiency may not apply uniformly across different concentration ranges, for example between grams of sample per litre in one analysis and mg/L in another.

Other studies report removing polystyrene from wastewater using the coagulants typically used in wastewater treatment, ferric chloride, polyaluminum chloride, and polyamine with success rates up to 99.4% when using ferric chloride and polyaluminum chloride (Rajala et al., 2020). However, with the high abundance of microplastics in all waters (treated or otherwise), copious more quantities of these coagulants would likely be needed for removing microplastics, which raises questions about costs and scale.

An alternative to the above methods that address the issues of scale, cost and environmental footprint would be employing natural flocculants. There are three types of flocculants based on their origin: natural, synthetic and semi-synthetic (Dey et al., 2021). Common natural flocculants include chitosan, starch, cellulose, tannin, microbial raw materials and animal glue and gelatin. They can also be further sub-classed into three categories depending on their surface charges as: i) cationic, ii) anionic and iii) non-ionic flocculants, reflecting the surface characteristics of the material (El-Gaayda et al., 2021).

'Green sourced' polysaccharides are a source of natural flocculants and these flocculants have already been used in water treatment. For example, mucilage extracted from *Tamarindus indica* pods has been applied for sulphate and phosphate ions in water, and with 74% and 76% removal, respectively (Mishra and Bajpai, 2006). Elsewhere, an anion-grafted starch-based flocculant has been demonstrated as having up to 99% flocculation removal rates of cationic pollutants like heavy metals (Kang et al., 2022). Similarly, flocculants from okra polysaccharides have been reported for treatment of palm oil mill effluent. The removal efficiencies of turbidity, total suspended solids and chemical oxygen demand were 94.97%, 92.70% and 63.11%, respectively (Lanan et al., 2021). In addition, the heteropolysaccharide BP50–2 comprising of mannose, rhamnose, glucuronic acid, galacturonic acid, glucose, galactose, and fucose at a molar ratio of 8.97:5.36:1.92:1.00:32.52:8.30:2.64, respectively has been extracted from natural sources like banana peel waste (Ma et al., 2022). Alginate, chitosan, cellulose, starch, pullulan, xanthan, and pectin to be the most common polysaccharides used as bio-flocculants (Maruyama and Seki, 2022).

Therefore, the removal of undesirable materials from water using natural, polysaccharide flocculants has consistently demonstrated high rates of success.

4.1. Challenges to removing microplastics from drinking water

Microplastics have been removed at a full-scale conventional drinking water treatment plant by combining coagulation with aluminum hydroxide, flocculation, anthracite-sand filtration, and chlorination (Cherniak et al., 2022). It was reported that coagulation, flocculation, and sedimentation accounted for 70% removal of microplastics which is lower than the 98% removal figure obtained by others in laboratory experiments using pondwater (Li et al., 2021). The variation may be due to the continuous disrupted by airborne deposition of more microplastics (Cherniak et al., 2022) and highlights a major obstacle to removal of microplastics at water treatment scale.

Conventional water treatment using coagulation/flocculation, sedimentation and sand filtration has been compared with using granular activated carbon filtration in removing microplastics from drinking water (Wang et al., 2020b). Conventional water treatment showed a removal efficiency of about 40.5–54.5%, mainly with plastic fibres, while the presence of granular activated carbon reduced the microplastic abundance by about 56.8–60.9%, mainly for small-sized microplastics. Polyacrylamide was also left in the water when coagulant was employed which could be a setback from health and environmental viewpoints (Wang et al., 2020b). Similarly, in a study of 5 μm – 5 mm granular microplastics and 100 μm – 5 mm fibrous microplastics, it has been found that only up to 81% of microplastics ≤20 μm (which accounts for <98% in raw waters) could be removed through conventional drinking water treatment processes (Wu et al., 2022). Only up to 43% of granular microplastics could be removed through conventional water treatment, however using biologically activated carbon filtration methods could achieve up to 64% removal. The reasons for these were attributed to varied size distribution of microplastics, further fragmentation of the microplastics (Wu et al., 2022).

4.2. Plastic use reduction - legal considerations and regulations

Globally, several restrictions have been placed on single-use plastic. In 2019, a restriction on plastics use has been made by the European Chemicals Agency (ECHA), and aims to ban products on the European market whose use is likely to release microplastics to the environment (Jung et al., 2022). It is believed that the ban would cover common

Fig. 7. Global ban or limit to use of plastic bags (2021). Image reproduced from Statistica (Buchholz, 2021) under Creative Commons License CC BY-ND 3.0.

household products such as laundry and cleaning products and cosmetics, apart from fertilizers, plant protection products, and seed coatings (Khan et al., 2022).

Nationally, the more common approach towards reducing plastic use has been through a ban or government initiatives for reducing plastic-based carrier bags such as shown in Fig. 7.

Legislation in some countries extends beyond plastic bags and includes single use plastic materials such as plastic straws, cutlery and plates (Mathew et al., 2023). Such bans have had mixed results, and for various reasons such as those listed by Muposhi et al. (2022). These include a lack of suitable alternatives, difficulties in the enforcement of the ban and ensuring compliance, and even the power of the plastic industry lobby against the bans. Then, there are also jurisdictional variations in the enforcement of the bans, such as in India where single-use plastic products were banned in 2022 but the implementation was left to the states (Nøklebye et al., 2023). Significant inconsistencies in plastic bag legislations can arise across states, as was evident in the United States where 19 states have pre-emptions prohibiting local governments from regulating plastic bags (Wang et al., 2022a). It has been argued that generally, when plastic bag ban policies are more stringent, consumer behaviour becomes more environmentally friendly (Wang et al., 2023). The imposition of absolute bans by the Fijian Government on single use plastic bags thinner than 50 μm (Government of Fiji, 2020) and higher taxes and levies on consumers such as in Australia where single use plastic bags were removed and thicker bags attracted a fee have also been known to reduce plastic bags consumption significantly. It is the latter that is considered the most effective, however (Adeyanju et al., 2021).

Amidst the complexity in the legislative landscape around microplastics, a one-size-fit-all approach may not be found. However, there are considerable learnings that can be applied form the success of previous mitigation agreements around pollutant emissions. The Montreal Protocol is an excellent example. Its success can be attributed to several factors. First, leadership and innovation led by scientists in the small, informal nature of the negotiation groups facilitated a genuine exchange of ideas. Second, as the science was still emerging around ozone depletion at the time of negotiating the Protocol, the flexibility of the framework enabled amendments to strengthen the controls as needed in the future. Third, trade provisions to encourage countries to sign up were successful motivators. Fourth, the "precautionary principle" of acting even amidst inconclusive science was a forward and innovative step that continues to be implemented today. Fifth, by clearly articulating the target chemicals responsible for ozone depletion were clearly articulated, and the same can apply to microplastics in the present situation. Sixth, and perhaps most importantly, the industry was allowed time to plan research and innovate their practices accordingly to phase out old technology (Rae, 2016). Thus, there are a lot of positive lessons from the Montreal Protocol that remain valid and relevant to a similar approach for microplastics.

5. Concluding remarks and future directions

In this review, we have covered several key aspects of microplastics in the global environment. These microplastics are predominantly in the form of polyethylene and polypropylene fibres, sourced from synthetic textiles, followed by bottles and packaging. While their major point sources are landfills and open dumps, microplastics are easily dispersed globally.

The environmental fate and health risks from microplastic particles depend on their physicochemical properties. While data on actual adverse effects on humans remains scarce, animal models do reveal toxic effects. In addition, the role of microplastics as carriers of other toxins such as heavy metals presents further challenges.

Continuing reliance on plastic will offset any measures being taken to reduce microplastics being released into the environment. Globally, there has been a concerted effort towards the eradication of single-use plastic bags in several countries, and this trend is likely to continue to expand. Changing waste disposal and other legal frameworks around emission of plastics would need to be a science and research-informed process.

Remediation and removal of plastic particles from the environment needs to become the next focus. This review has demonstrated that microplastics permeation into all environments on Earth makes it virtually impossible to evade their exposure. Therefore, there needs to be a parallel research effort towards the sustainable removal of microplastics, rendering the environment as safe. The removal from drinking waters needs to become a priority, and much potential for this can be obtained from green remediation methods.

CRediT authorship contribution statement

Shaneel Chandra: Writing – review & editing, Writing – original draft, Visualization. **Kerry B. Walsh:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used no AI or AI-assisted technologies in the writing process.

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

Data will be made available on request.

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