Water Supply

IWA PUBLISHING

Water Supply Vol 22 No 5, 5650 doi: 10.2166/ws.2022.189

Microplastics in drinking water: a macro issue

Surya Singh [a,*], Tanwi Trushna[b], Madhanraj Kalyanasundaram[b], Ashok J. Tamhankar[c,d] and Vishal Diwan[a]

[a] Division of Environmental Monitoring and Exposure Assessment (Water & Soil), ICMR – National Institute for Research in Environmental Health, Bhopal 462 030, India
[b] Division of Environmental Health and Epidemiology, ICMR – National Institute for Research in Environmental Health, Bhopal 462 030, India
[c] Department of Global Public Health, Health Systems and Policy (HSP): Medicines Focusing Antibiotics, Karolinska Institutet, Stockholm 17177, Sweden
[d] Indian Initiative for Management of Antibiotic Resistance, 302, Aryans, Deonar farm road, Deonar, Mumbai 400 088, India
*Corresponding author. E-mail: suryasingh.nireh@icmr.gov.in

SS, 0000-0001-5981-2343

ABSTRACT

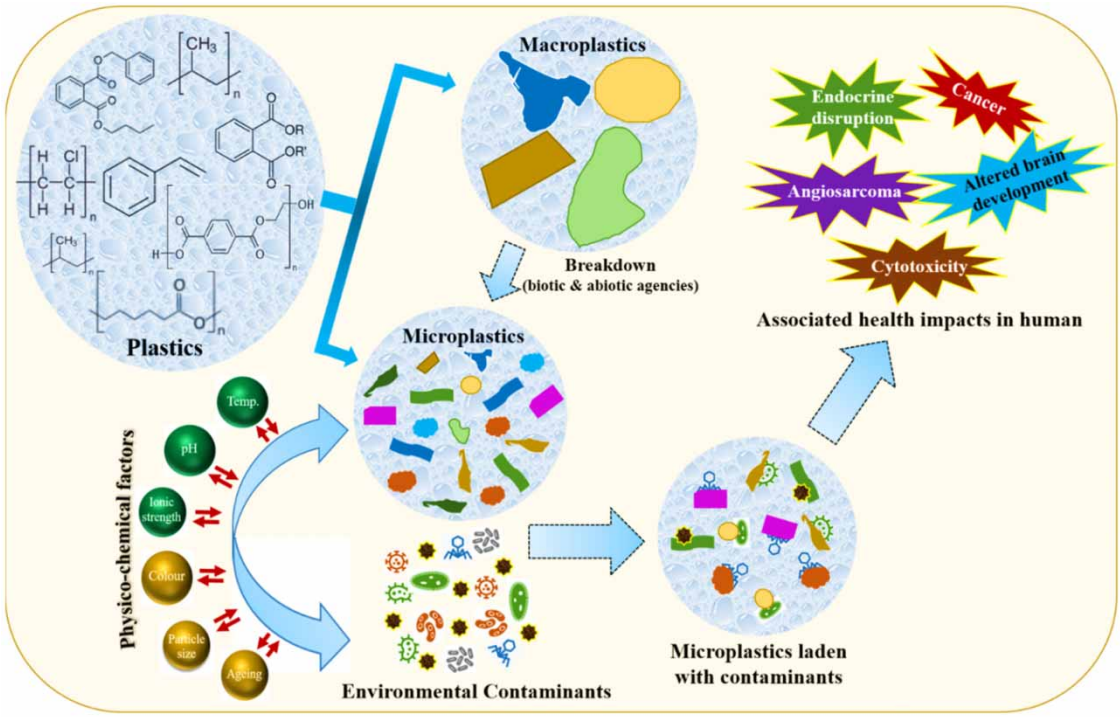
Microplastics are one of the emerging contaminants that have received attention in recent decades due to their adverse effects on human health and the environment. Though microplastics are primarily found in abundance in oceans, freshwater sources and drinking water are not unaffected. Nevertheless, it is not only the microplastics that are harmful; rather their ability to transport contaminants is another serious issue of concern. The contaminant transport ability is affected by various environmental and physico-chemical parameters of microplastics. Lack of effective and targeted water treatment technologies have led intake of microplastics by humans resulting in a variety of health issues. Even though a few regulatory attempts have been made in the direction of curtailing the production and use of microplastics, there is still a long way to go. This paper focuses on various aspects of microplastics' presence in drinking water, focusing on their contaminant transport ability, human health risks, removal technologies, and the global scenario of concern.

Key words: drinking water, emerging contaminants, environmental factors, human health, microplastic(s)

HIGHLIGHTS

- Global production of plastics has increased from 1.5 million tons in 1950 to 359 million tons in 2018.
- Microplastics act as the carrier of a variety of organic/inorganic contaminants and pathogens in drinking water.
- Contaminant transport ability is influenced by environmental and physico-chemical properties of microplastics.
- Microplastics in drinking water might trigger a variety of adverse health impacts.

GRAPHICAL ABSTRACT



INTRODUCTION

Plastics are an important material in today's world considering their remarkable physical and chemical properties, inertness, wide-scale usability, and reusability. Realizing the potential of plastics, its production has increased globally from 1.5 million tons in 1950 to 359 million tons in 2018 (Garside 2019; Plastics Europe 2019) (Figure 1). Despite having numerous benefits, plastics are associated with myriad environmental and human health issues due to their extremely slow biodegradation in nature and release of poisonous chemicals upon burning (Thornton *et al.* 1996; Sindiku *et al.* 2015; Ni *et al.* 2016; Rajmohan *et al.* 2019). In many of the countries a significant portion of plastic waste is discarded as such, instead of being recycled or incinerated (Geyer *et al.* 2017; Plastics Europe 2019) (Figure 1). The discarded plastic waste accumulated over land sources, agricultural land, stagnant water bodies, and wastewater effluent/sludge, finds its way into the rivers. It has been estimated that approximately 70–80% of plastic waste from land based sources, which is approximately 1.15–2.41 million tons, is carried away by the rivers, and ultimately ends up in the oceans (Horton *et al.* 2017; Lebreton *et al.* 2017). The major contributors are the Asian rivers amounting to approximately 67% of the global total (Lebreton *et al.* 2017). Breakdown of this plastic waste over time through the action of waves and winds results in the formation of microplastics. Microplastic is a relatively new term and an emerging contaminant, which is defined as synthetic plastic polymer having an upper size limit of 5 mm (Arthur *et al.* 2009; Thompson *et al.* 2009). While dealing with discarded plastic waste is still a significant global public health challenge, discovering the role of microplastics as an emerging pollutant of concern is another issue for the environmental health stakeholders.

Based on their origin, microplastics can be categorized into primary and secondary microplastics. Primary microplastics are intentionally manufactured in sizes <5 mm to be used in various applications such as cosmetics, clothing and other textiles, fishing nets, etc. (Mai *et al.* 2018). However, secondary microplastics originate from the breakdown of discarded plastic waste by solar radiation, mechanical degradation, microbial action, etc. (Rodrigues *et al.* 2018; Wagner & Lambert 2018). These microplastic particles may be of various shapes such as fragments, pellets, beads, and fibres. The occurrence of microplastics has been reported from oceans, sediments, freshwater, wastewater, tap water, bottled water, air, food products, aquatic organisms, *etc.* (WHO 2019). The prevalent units used to express microplastics' abundance in water, sediment, and biota are particles/m^3 (or particles/L), particles/m^2, and particles/individual, respectively (Mai *et al.* 2018).

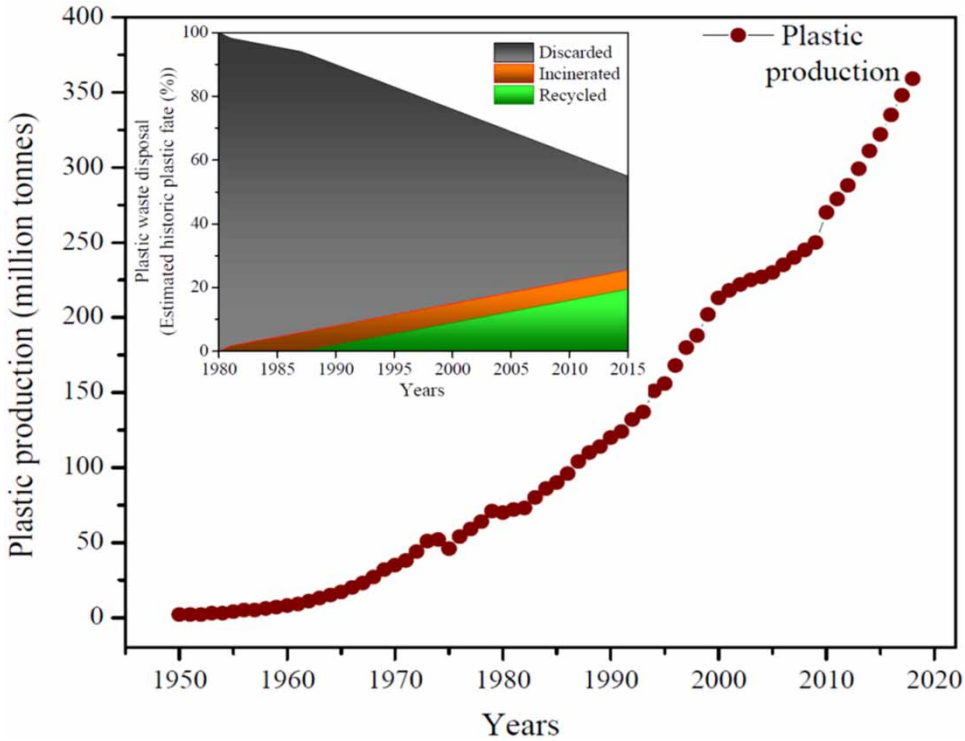


Figure 1 | Trends in global primary plastic production and methods of plastic waste management. (*Data source:* Geyer *et al.* 2017; Plastics Europe 2019).

The identification and quantification of microplastics have been carried out using various techniques such as microscopy, spectroscopy, and chromatography. The simplest and the most common technique to identify and quantify microplastic particles is optical microscopy, where quantification is achieved through manual counting. Though this technique is simple, it poses limitations in terms of misidentification and reduced accuracy (underestimation (Loder *et al.* 2015)/overestimation (Lenz *et al.* 2015)). However, application of electron microscopic techniques, such as scanning electron microscopy, may overcome this limitation to some extent (Eriksen *et al.* 2013). Application of spectroscopic analysis is more pertinent considering that spectroscopic techniques can identify the chemical composition of microplastics and hence can differentiate among the varieties of microplastic particles. Fourier transform infrared spectroscopy (Kosuth *et al.* 2018; Schymanski *et al.* 2018; Mintenig *et al.* 2019) and Raman spectroscopy (Oβmann *et al.* 2018; Pivokonsky *et al.* 2018) are utilized for this purpose. The combination of microscopic and spectroscopic techniques further enhances the output (Pivokonsky *et al.* 2018). Apart from these, researchers have used some new techniques as well for the identification of microplastics, such as pyrolysis gas chromatography mass spectroscopic (GC-MS) techniques (Fries *et al.* 2013; Peters *et al.* 2018; Fischer & Scholz-Bottcher 2019; Funck *et al.* 2020). In contrast to microscopic and spectroscopic techniques, the pyrolysis GC-MS technique is a destructive one, where a sample needs to be pyrolyzed to get it identified. Moreover, this technique fails to provide information regarding the number, type, and morphology of the particles (Hanvey *et al.* 2017). Pressurized fluid extraction is another technique for the quantification of microplastic particles where semi-volatile organics are obtained from solid plastic materials at sub-critical temperature and pressure (Fuller & Gautam 2016). A detailed review on identification and quantification techniques of microplastics is provided by Hanvey *et al.* (2017).

The microplastics are of immense environmental and public health concern because of their inherent physico-chemical properties and ubiquitous presence as well as persistence (Rezania *et al.* 2018; Xu *et al.* 2018a). Moreover, microplastics also leach out various persistent organic pollutants, which are of serious health concern (Silva *et al.* 2018). Microplastics may pose health impacts in three ways: (1) the particles themselves, as these are small and can be ingested/inhaled easily; (2) various chemicals which are present in microplastics such as sorbed moieties, additives, etc.; and (3) microorganisms, which get attached to and colonize over the microplastics and result in biofilm formation (WHO 2019). Thus, microplastics act as a carrier of various hazardous moieties/organisms and affect biotic species including the human beings. Their

contaminant transport ability is governed by various environmental and physico-chemical properties. For example, acidic pH helps in adsorption of a variety of the contaminants (Holmes *et al.* 2014; Li *et al.* 2019; Wang *et al.* 2020a), while the presence of dissolved organic matter reduces the adsorption (Wu *et al.* 2016; Xu *et al.* 2018b). This happens because pH and dissolved organic matter affect the basic properties of chemicals (contaminants) such as pKa and hydrophilicity. Similarly, small particle size and low density of microplastics promote the sorption of contaminants and *vice-versa* (Mato *et al.* 2001, 2002; Teuten *et al.* 2007; Liu *et al.* 2018a; Wang *et al.* 2018; Li *et al.* 2019).

The occurrence of microplastics in marine environment is widely recognized and documented (Barboza & Gimenez 2015; Galloway & Lewis 2016; Wright & Kelly 2017; Carbery *et al.* 2018; Karthik *et al.* 2018; Rezania *et al.* 2018; Smith *et al.* 2018; Wang *et al.* 2018; Ashwini & Varghese 2020; Robin *et al.* 2020). However, there are very few comprehensive studies/reports about the occurrence of microplastics in drinking water (Kosuth *et al.* 2018; Schymanski *et al.* 2018; Eerkes-Medrano *et al.* 2019; Koelmans *et al.* 2019; Novotna *et al.* 2019). Considering the human health aspects, drinking water is one of the most important sources through which microplastics can be ingested. Therefore, it is necessary to understand various environmental and physico-chemical factors that might affect the microplastics' transport and possible health impacts of microplastics found in drinking water. In this paper, occurrence of microplastic particles in drinking water has been reviewed. Aspects covered in this context are – the origin of microplastics, environmental and physico-chemical factors associated with microplastics' occurrence and contaminating ability, human health impacts, possible removal methods, and actions taken for curtailing the production and use of the same.

MICROPLASTICS: ORIGIN AND PATHWAYS TO REACH UP TO DRINKING WATER

Microplastics (both primary and secondary) pollute drinking water sources primarily through discharge of sewage/wastewater treatment plant effluent and surface run-off (Figure 2). There are large numbers of industries that use (primary) microplastics for various applications, such as medicines, cosmetics, etc. After their use, these primary microplastics get washed off and become a part of the domestic wastewater (Singh *et al.* 2021). As the sewage/wastewater treatment plants are not equipped for the complete removal of microplastics, the effluent released from these plants contains substantial quantity of microplastics (Amrutha & Warrier 2020). Upon mixing of this effluent with the freshwater sources, microplastics become part of the fresh/drinking water supply chain (Magnusson & Noren 2014; Novotna *et al.* 2019; Okoffo *et al.*

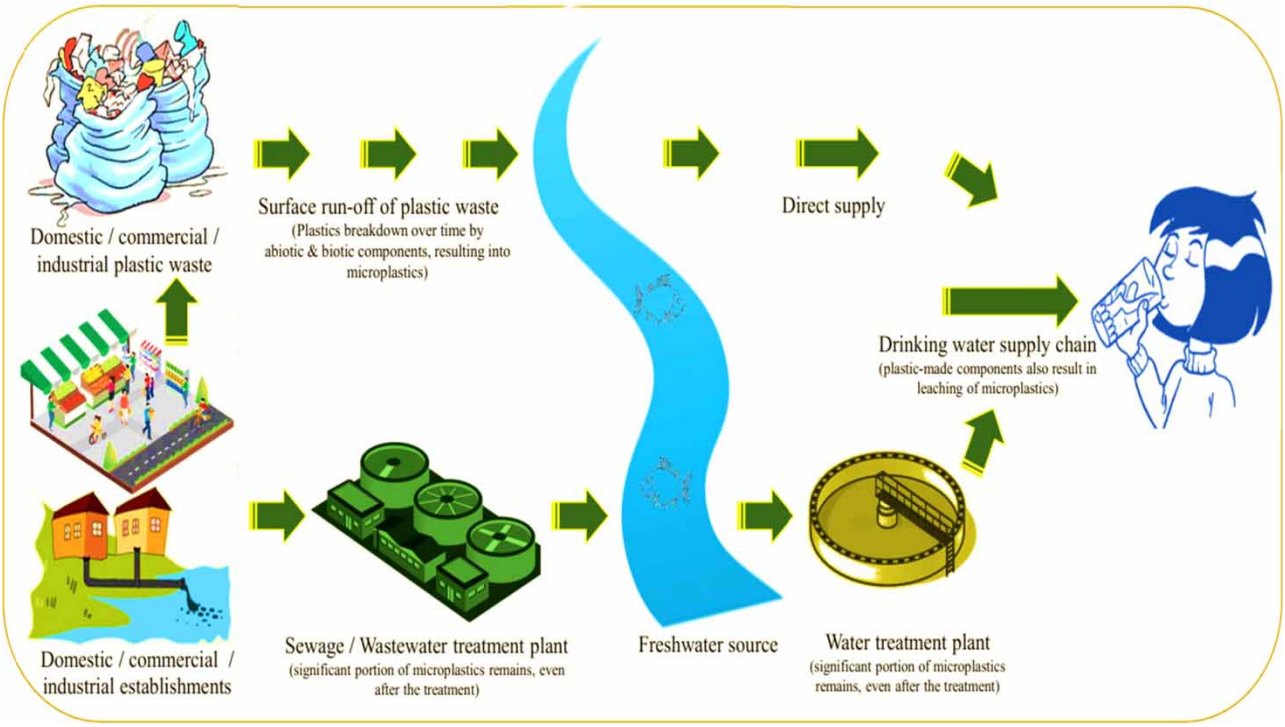


Figure 2 | Origin of microplastics and pathways to reach up to the drinking water.

2019). For example, increase in the concentration of microplastics in the Chicago River has been reported to be due to the local wastewater treatment plants' effluent (McCormick *et al.* 2014). It is also important to note that many components of water treatment plants and water distribution system are usually made up of plastic materials, such as high density polyethylene, polyvinyl chloride, polypropylene, etc. (Mintenig *et al.* 2019) and hence, these further contribute towards microplastic generation in the water they carry.

Treated bottled water is also reported to contain microplastics (Mason *et al.* 2018; O*β*mann *et al.* 2018; Pivokonsky *et al.* 2018; Schymanski *et al.* 2018). Mason *et al.* have reported that approximately 10.4 microplastic particles have been found in a litre of bottled drinking water, with size of more than 100 μm (Mason *et al.* 2018). Nevertheless, the smallest microplastic particle reported in case of drinking water is 1 μm (WHO 2019). Evidence suggests that it is the bottling process and/or packaging of the plastic bottles/caps that largely contributes to the generation of microplastics. It has been found that water from the same source shows more microplastics when it is packaged in plastic bottles, as compared to one packaged in glass bottles (Mason *et al.* 2018; Schymanski *et al.* 2018). Polypropylene is the most common type of microplastic found in bottled water (Mason *et al.* 2018). However, another study revealed that a mix of polyester and polyethyleneterephthalate is most commonly found in single-use plastic bottles (Schymanski *et al.* 2018). By and large, microplastics in drinking water are the outcome of improperly disposed plastic materials and plastic packaging. A summary of the occurrence of microplastic particles in drinking water is presented in Table 1.

Though a significant portion of microplastics in drinking water is contributed by the primary microplastics (~ 15–31%), the proportion contributed by the secondary microplastics is huge, which amounts to approximately 69–81% (EU 2018). These secondary microplastics originate through the breakdown of macroplastics in landfills and open dumping sites (Rillig 2012; Duis & Coors 2016; Liu *et al.* 2018b; Rodriguez-Seijo & Pereira 2018). The leachate generated from these sites contains significant amounts of microplastics which seep along with the water and contaminate the freshwater as well as groundwater sources. This is the reason why not only the drinking water obtained from surface water sources is contaminated, but also the water extracted from the ground is found to contain microplastics, though in lesser quantities (Mintenig *et al.* 2019).

Breakdown of macroplastics to (secondary) microplastics is largely influenced by the environmental factors, such as sunlight, temperature, air/oxygen, etc. The impact of these factors on the breakdown process indicates that the process varies from place to place, as different locations have different environmental features (Weinstein *et al.* 2016). It has been seen that polyethylene materials degrade faster in air, as compared to seawater, because of the difference in temperature, oxygen content, and sunlight exposure (Pegram & Andrady 1989; Andrady *et al.* 1993). Moreover, weathering is slow in submerged habitats because of the fast reduction of UV-B radiation, biofilm formation, low temperature, and oxygen content (Andrady 2011).

MICROPLASTICS: CARRIER OF CONTAMINANTS

Role of microplastics as carrier of contaminants

The microplastics are not only harmful per se, but act as source and sink for many other contaminants as well. Microplastics themselves act as source of various chemicals, additives, and pigments, which are added during the manufacturing process of the plastics. Further, microplastics also adsorb a variety of inorganic and organic contaminants such as persistent organic pollutants, metals/metalloids, pesticides, pharmaceuticals, microorganisms, etc. and hence also act as a sink. Several authors have reported that microplastics act as an important carrier for transportation of heavy metals, particulate matter, persistent organic pollutants, etc. (Brennecke *et al.* 2016; Kwon *et al.* 2017; Yu *et al.* 2019; Barbosa *et al.* 2020). Moreover, the sorption depends on various factors such as, physicochemical properties of the polymer, surrounding environment, atmospheric temperature, humidity, salinity, weathering, ageing processes, etc. As microplastics get weathered with time due to the effect of various environmental factors, their ability to transport contaminants also gets affected (Hartmann *et al.* 2017) which further enhances threat for the drinking water sources. Additionally, plastic debris gain more surface area upon weathering, thus generating oxygen groups that collectively affect their polarity, roughness, charge, and porosity; thereby enhancing the adsorption capacity (Fotopoulou & Karapanagioti 2012). Surface charge, surface area, functional groups, and acid-base characteristics also influence the sorption of contaminants on the microplastics' surface (Fred-Ahmadu *et al.* 2020).

Colonization of microorganisms over microplastics present in the aquatic system is another important aspect that has been looked into (Harrison *et al.* 2014). Microplastic surfaces are known to promote the survival and growth of a wide variety of microorganisms (Wu *et al.* 2019). Various antibiotic-resistant genes as well as human pathogens have been detected on the

Table 1 | Microplastics contamination in drinking water reported across the globe (*Adapted from* Singh *et al.* 2021)

Type of water	Identification method	Size range (μm)	Concentration (particles/L)	Morphology	Composition	References
Ground drinking water sources	FTIR spectroscopy[a]	50–150	0–7	Fragments	Polyethylene, polyamide, polyester, polyvinylchloride	Mintenig *et al.* (2019)
	Pyrolysis – GC MS[a]	–	6.4	Fibres	Polyethylene	Panno *et al.* (2019)
Treated water from water treatment plants	FTIR spectroscopy & micro-Raman imaging microscopy	1–10	338 ± 76 to 628 ± 28	Fragments, fibres	Polyethylene terephthalate, Polypropylene, Polyethylene	Pivokonsky *et al.* (2018)
Tap water	FTIR spectroscopy	100–5,000	0–61	Fibres	–	Kosuth *et al.* (2018)
Plastic bottled water	FTIR spectroscopy	6.5 – >100	0 to >10,000	Fragments, fibres	Polypropylene	Mason *et al.* (2018)
		–	3.57	Fibres	–	Kosuth *et al.* (2018)
	Micro – FTIR spectroscopy	5–20	118 ± 88 (returnable bottles), 14 ± 14 (single-use bottles)	Fragments	Polyethylene terephthalate, Polypropylene	Schymanski *et al.* (2018)
	Micro – Raman spectroscopy	< 5	4,890 ± 5,430 (returnable bottles) 2,649 ± 2,857 (single-use bottles)	–	Polyethylene	Oβmann *et al.* (2018)
Glass bottled water	FTIR spectroscopy	6.5 – >100	1,410 14.8 (>100 μm) 1,396 (6.5–100 μm)	Fragment, fibre, pellet, film, foam	–	Mason *et al.* (2018)
	Micro – FTIR spectroscopy	>100	50 ± 52	–	Polyamide, Polyethylene, Polypropylene	Schymanski *et al.* (2018)
	Micro – Raman spectroscopy	<5	6,292 ± 10,521	–	Polyethylene, Styrene – butadiene – copolymer	Oβmann *et al.* (2018)
Cardboard bottled water	Micro – FTIR spectroscopy	>100	11 ± 8	Fibres	Cellulose, Polyethylene, Polypropylene	Schymanski *et al.* (2018)

[a]FTIR: Fourier Transform Infra-Red (FTIR) Spectroscopy; GC MS: Gas Chromatography Mass Spectrometry.

surface of microplastic particles (Wu *et al.* 2019). The first report of microplastic colonization by microbes appeared in the 1970 s, where white plastic pellets were found to be associated with diatoms and hydroids (Carpenter & Smith 1972; Carpenter *et al.* 1972). Virsek *et al.* have reported the presence of the bacterial fish pathogen *Aeromonas salmonicida* (syn *Haemophilus piscium*) on the surface of microplastics (Virsek *et al.* 2017). The reason behind the attachment of microbes on the microplastics is that any solid surface present in an aquatic environment is prone to absorb a variety of nutrients that attract the microbes (Oberbeckmann *et al.* 2015). An excess of nutrients over the microplastic particles acts as hotspots and competition may also develop among the microbes to obtain it (Hall-Stoodley *et al.* 2004; Salta *et al.* 2013). The microbe-laden microplastics, when ingested by humans, have the potential to cause various health-related issues such as endocrine disruption, cytotoxicity, etc.

The biofilm formation is also found responsible for the adsorption of metals over the microplastics' surface. It has been shown that all the metals, irrespective of space and time, do get adsorbed on the microplastics (Johansen *et al.* 2018). Later it was suggested that this accumulation might be controlled by the biofilm formation, and the distribution of biofilm is similar among the variety of plastics. Therefore, it allows all types of metals to get adsorbed on most of the plastics (Johansen *et al.* 2018).

Effect of environmental parameters on the contaminant transport capacity of microplastics

Many environmental parameters affect the contaminant transport capacity of the microplastics, such as, pH, temperature, salinity, organic matter, etc. (Figure 3). pH is one of the important factors to consider as it has been reported that high pH results in decreased sorption of some antibiotics and surfactants on the surface of metals, while decreasing pH has the opposite effect (Holmes *et al.* 2012, 2014; Wang *et al.* 2015; Guo *et al.* 2018). Increase in pH results in a high concentration of hydroxide (OH^-) ions. Interaction of OH^- ion with the various ionic forms of the contaminant decides the sorption behaviour. The ionic strength of the medium is another important parameter that represents the charge associated with it (Zhang *et al.* 2018; Hu *et al.* 2020). This property might increase or decrease the sorption depending upon the ionic strength of the medium and type of contaminant involved, as well as synergistic and/or antagonistic interaction with other parameters (Brewer *et al.* 2020). The mechanism involved here is the shrinkage of the plastic polymer upon increasing the ionic strength, which causes a reduction in the pore size as well as the number of adsorption sites, thereby reducing the adsorption (Xu *et al.* 2008; Dong *et al.* 2020a). Solar radiation also results in the breaking of bonds in the polymers, which increases the surface area and pore size of the microplastics, thereby allowing more adsorption of organic moieties over microplastics (Kalogerakis *et al.* 2017).

Temperature and salinity are other environmental parameters that affect the sorption of contaminants on the microplastics. The vander Waals force among the molecules is the deciding factor, as it decreases upon increasing the temperature owing to faster mobility and solubility of molecules at higher temperatures (Gusso & Burnham 2016) which results in enhanced sorption (Table 2). Contrary to this, it has also been seen that after a certain point, high temperature also reduces surface tension, which ultimately results in low sorption of contaminants (Liu *et al.* 2018a). As far as salinity is concerned, it might not affect the freshwater sources directly; however, it affects the microplastics' contaminant carrying ability in marine environment (Hu *et al.* 2017; Liu *et al.* 2018a, 2019). Thus, microplastics that pass on from marine environment to surface/ground water resources through

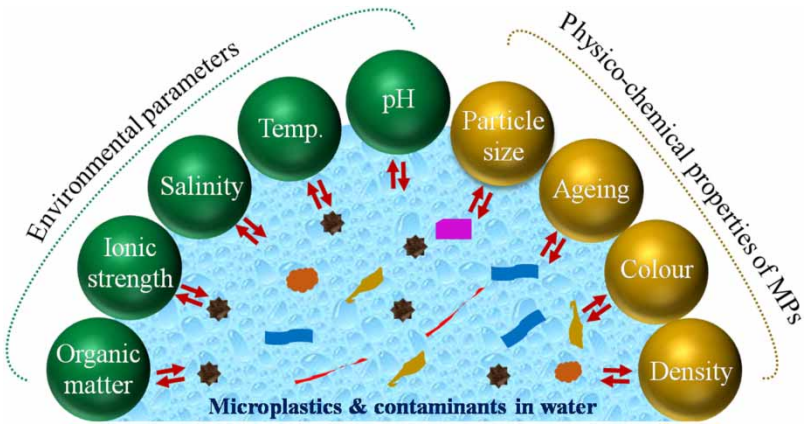


Figure 3 | Factors affecting the transport of contaminants by microplastics (MPs).

Table 2 | Environmental parameters affecting contaminant transport by microplastics

Type of microplastic	Type of contaminant sorbed	Change in parameter	Impact on contaminant sorption on MPs	References
pH				
Polystyrene	Metalloid (Arsenic)	Increase (pH 3→7)	Decreased	Dong *et al.* (2020a)
Polyethylene	Pesticides (Carbendazim, Dipterex)	Increase (pH 2→6)	Decreased	Wang *et al.* (2020a)
	Pesticides (Malathion)	Increase (pH 2→3)	Increased	
	Pesticides (Diflubenzuron, Difenoconazole)	Increase (pH 2→6)	Increased	
Polytetrafluoroethylene	Metalloid (Arsenic)	Increase (pH 3→7)	Decreased	Dong *et al.* (2019)
Polystyrene	Broad spectrum antimicrobial and endocrine disrupting chemical (Triclosan)	Increase (pH 3→6) Increase (pH 6→12)	Increased Decreased	Li *et al.* (2019)
Polystyrene, Polyvinylchloride	Antibiotic (Tylosin)	Increase (pH 3→7)	Decreased	Guo *et al.* (2018)
Polyethylene, Polypropylene, Polystyrene	Antibiotic (Tetracycline)	Increase (pH 2→6)	Increased	Xu *et al.* (2018b)
Polyethylene	Antibiotic (Sulfamethoxazole)	Increase (pH 2→12)	Increased (slightly)	Xu *et al.* (2018c)
Polyethylene, Polystyrene	Lubrication oil	Increase (pH 1→10)	Independent of pH	Hu *et al.* (2017)
Polyethylene (virgin and beached)	Metals (Ag, Cd, Co, Ni, Pb, Zn) Metal (Cr) Metal (Cu, Hg)	Increase (pH 4→10)	Increased Decreased Unclear	Turner & Holmes (2015)
Polyethylene, Polystyrene	Surfactant (Perfluorooctanesulfonic acid)	Decreasing	Increased	Wang *et al.* (2015)
High density polyethylene	Metals (Cd, Co, Ni, Pb) Metals (Cr)	Increasing	Increased Decreased	Holmes *et al.* (2014)
Ionic Strength				
Polystyrene	Polycyclic hydrocarbons (Naphthalene)	Up to 0.5 mM 5 mM – 50 mM	Increased Decreased	Hu *et al.* (2020)
Polystyrene	Metalloid (Arsenic)	Increased	Decreased	Dong *et al.* (2020a)
Polyethylene	Pesticides (Carbendazim, Dipterex, Malathion, Diflubenzuron, Difenoconazole)	Increased	Increased	Wang *et al.* (2020a)
Polytetrafluoroethylene	Metalloid (Arsenic)	Increase (0 M→1 M)	Decreased	Dong *et al.* (2019)
Polystyrene	Antibiotic (Oxytetracycline)	Increased	Decreased	Zhang *et al.* (2018)
Polystyrene, Polyvinylchloride, Polypropylene, Polyethylene	Antibiotic (Tylosin)	Increase (0 M→0.1 M) Increase (>0.1 M)	Increased Decreased	Guo *et al.* (2018)

(*Continued.*)

Table 2 | Continued

Type of microplastic	Type of contaminant sorbed	Change in parameter	Impact on contaminant sorption on MPs	References
Salinity				
Polyethylene, Polystyrene, Polypropylene, Polyamide, Polyvinylchloride	Antibiotics (Ciprofloxacin, Amoxicillin)	Presence of salt	Decreased	Liu *et al.* (2019), Li *et al.* (2018a)
Polyethylene	Antibiotic (Sulfamethoxazole)	Increase (0.05%→3.5%)	Independent of salinity	Xu *et al.* (2018c)
Polypropylene	Brominated flame retardants (Tris-(2,3-dibromopropyl) isocyanurate (TBC) and Hexabromocyclododecanes (HBCDs))	Increase (0.05%→14%) Increase (14%→21%)	Increased Decreased	Liu *et al.* (2018b)
Polyethylene, Polystyrene	Lubrication oil	Increase (0.001→0.1 mol/L)	Increased	Hu *et al.* (2017)
Polyethylene, Polyvinylchloride	Pesticide (DDT)	Presence of salt	Decreased	Bakir *et al.* (2014)
High density polyethylene	Metals (Cd, Co, Ni) Metals (Cr) Metals (Cu, Pb)	Increasing	Decreased Increased independent of salinity	Holmes *et al.* (2014)
Temperature				
Polystyrene	Broad spectrum antimicrobial and endocrine disrupting chemical (Triclosan)	Increase (15 °C→45 °C)	No effect	Li *et al.* (2019)
Polytetrafluoroethylene	Metalloid (Arsenic)	Increase (15 °C→35 °C)	Decreased	Dong *et al.* (2019)
Polypropylene	Brominated flame retardants (Tris-(2,3-dibromopropyl) isocyanurate (TBC) and Hexabromocyclododecanes (HBCDs))	Increase (5 °C→15 °C) Increase (15 °C→45 °C)	Increased Decreased	Liu *et al.* (2018b)
Dissolved Organic Matter (DOM)				
Polyethylene, Polypropylene, Polystyrene	Antibiotic (Tetracycline)	Addition of DOM (fulvic acid)	Decreased	Xu *et al.* (2018b)
Polyethylene	Antibiotic (Sulfamethoxazole)	Addition of DOM (0→20 mg/L)	No significant effect	Xu *et al.* (2018c)
Polyethylene	Pharmaceuticals and personal care products (Carbamazepine, triclosan, 17α-ethinyl estradiol)	Addition of DOM	Decreased	Wu *et al.* (2016)

mixing, sea-water intrusion, and/or through biotic species, are of concern. It has been reported that with increasing salinity, lubricating oil gets adsorbed more on the polyethylene and polystyrene microplastics because of the ease of the outer-sphere surface complexation provided by the salts (Hu *et al.* 2017). Enhancement in the sorption capacity of contaminants over microplastics upon increasing the salinity implies that microplastics occurring in the marine environment are more prone to carry the contaminants (Velzeboer *et al.* 2014; Wang *et al.* 2015). However, this effect varies in the case of metals. The adsorption capacity for a few metals decreases with an increase in salt content, while it increases for others (Table 2). It has been postulated that competition for the sorption sites on the microplastic pellets is the determining factor for sorption (Holmes *et al.* 2014; Liu *et al.* 2018a). Influence of salinity also results in alteration in the agglomeration behaviour of microplastics which further influences the size and area related properties (Velzeboer *et al.* 2014).

Wu *et al.* studied the transport of some personal care products and pharmaceuticals through polyethylene. It was found that the presence of dissolved organic matter significantly reduces the sorption capacity of microplastics for these contaminants

(Wu *et al.* 2016) (Table 2). It happens because of the competition between organic matter and contaminants to get the sorption sites on microplastics (Cox *et al.* 2007). Moreover, there is also a possibility of the sorption of contaminants over the organic matter (Ilani *et al.* 2005; Wu *et al.* 2016). In such a scenario, adsorption of contaminant laden organic material over the microplastics may pose further risk. Nevertheless, some environmental factors help in reducing the sorption of organic compounds over microplastics. For example, interaction of microplastic particles with oxygen enhances the surface polarity in particles, which reduces the adsorption of organic moieties (Huffer *et al.* 2018). Similarly, weathering processes result in increased crystallinity of microplastic particles thereby helping in reducing the adsorption (Hartmann *et al.* 2017).

Environmental factors not only play a significant role in the transfer of chemical contaminants through microplastics; rather, colonization of microbial communities over the surface of microplastics is also affected considerably by the changes in environmental parameters (McCormick *et al.* 2014; Oberbeckmann *et al.* 2018). One of the reasons is that plastic surfaces are comparatively more stable than other natural materials and hence provide a stable base to microbes. Further, biogeography and seasonal variation in temperature and/or salinity have an important role in deciding the type of communities colonizing over the microplastics (Fuhrman *et al.* 2008; Oberbeckmann *et al.* 2012, 2014; Amaral-Zettler *et al.* 2015). A summarized list of various environmental parameters affecting the sorption of contaminants over microplastics is shown in Table 2.

Effect of physico-chemical properties of microplastics on their contaminant transport capacity in drinking water matrices

Physico-chemical properties of microplastics such as chemical composition, crystal structure, size, colour, density, *etc*. have a profound impact on their contaminant transport ability (Table 3). In general, microplastics possess higher sorption capacity for hydrophobic contaminants (Yu *et al.* 2019). Hydrophobic contaminants are usually lipophilic, and hence tend to sorb more on the microplastics, compared to the hydrophilic contaminants (Takada 2006). Specifically, these are found to dominate for sorption onto the polyethylene, polystyrene, and polyvinylchloride (Wang *et al.* 2015). Polyaromatic hydrocarbons (PAHs) are the typical hydrophobic pollutants in the environment. Strong interaction between PAHs and micro- or nanoscale plastics has been evidenced in aquatic environment (Tan *et al.* 2019). Hydrophobic interaction also plays an important role in the sorption behaviour of polychlorinated biphenyls (PCBs) such as diaclor, diconal, educarel, etc. over the microplastics. It has been shown that the sorption of PCBs on polyethylene plastic films was significantly higher than that of polystyrene and polyvinyl chloride. Later, these chemical-laden microplastics may get transferred to aquatic biota and further into the food chain through ingestion, sorption, and/or respiration (Hartmann *et al.* 2017). Therefore, it is important to understand the interaction behaviour of microplastics as well as contaminants. The sorption isotherms of various microplastics provide insights into their sorption behaviour. Sorption isotherms of polyethylene were found to be highly linear, which indicated that the sorption behaviour tended towards sorption into the bulk polymer. However, the sorption isotherms of polystyrene were nonlinear and $\pi - \pi$ interaction played a crucial role in the adsorption (Huffer & Hofmann 2016). The sorption isotherms of perfluorooctanesulfonic acid and perfluorooctanesulfonamide on the three different types of microplastics, *viz*. polyethylene, polystyrene, and polyvinylchloride, were highly linear, which revealed that the dominant interaction process was partitioning rather than hydrophobicity (Wang *et al.* 2015).

The porous and non-porous nature of microplastics is also important to determine its interaction with the contaminants. Some microplastics are non-porous (such as polyethylene) while others may be meso-porous (such as polystyrene). The non-porous nature of polyethylene results in higher sorption capability for hydrophobic organic compounds (Wang & Wang 2018; Zuo *et al.* 2019). On the other hand, the high sorption affinity of polystyrene for PAHs is attributed to the amorphous structure (Rochman *et al.* 2013). Similarly, it has also been reported that crystalline structure of microplastics reduces the adsorption of contaminants. The reason crystalline structures resist adsorption while amorphous structures favour it lies in the fact that it takes huge amounts of energy to destabilize the well-oriented polymer chains of crystalline structures (Liu *et al.* 2019). Similarly, the surface polarity of microplastics is another property that has an influence. The strength of interaction of the contaminants with the microplastics can be determined by the surface polarity of the microplastics, such as hydrophobic organic contaminants adhere more to the non-polar surfaces and vice-versa (Mato *et al.* 2002; Fred-Ahmadu *et al.* 2020). Further, the high surface area and small size can also enhance the adsorption capacity owing to more availability of active sites for adsorption (Yu *et al.* 2019).

The density of the microplastics influences sorption behaviour as well (Wang *et al.* 2018). The sorption process can be evaluated in terms of diffusion coefficients. Higher diffusion coefficient results in more sorption and vice-versa. It has been demonstrated in a study that pollutants have low diffusion coefficients in high-density polyethylene while high diffusion

Table 3 | Physico-chemical properties of microplastics affecting contaminant transport

Type of microplastic	Type of contaminants sorbed	Change in parameter	Impact on contaminant sorption on MPs	References
Particle size				
Polystyrene	Broad spectrum antimicrobial and endocrine disrupting chemical (Triclosan)	Decrease	Increased	Li *et al.* (2019), Wang *et al.* (2018)
Polypropylene	Brominated flame retardants (Tris-(2,3-dibromopropyl) isocyanurate (TBC) and Hexabromocyclododecanes (HBCDs))	Decrease	Increased	Liu *et al.* (2018b)
Polypropylene	Fungicide (Difenoconazole)	Decrease	Increased	Goedecke *et al.* (2017)
Ageing				
Polypropylene	Broad spectrum antimicrobial and endocrine disrupting chemical (Triclosan)	Increase	Increased	Wu *et al.* (2020)
Polypropylene	Benzene, toluene, ethylbenzene, and xylene (BTEX)	Increase	Independent of ageing	Muller *et al.* (2018)
Polystyrene	BTEX	Increase	Decreased	
Polypropylene	Fungicide (Difenoconazole)	Increase	Increased	Goedecke *et al.* (2017)
Resin pellets (along beaches)	Pesticide (DDT)	Increase	Increased	Antunes *et al.* (2013)
Polypropylene	Polyaromatic hydrocarbon (Phenanthrene)	Increase	Increased	Karapanagioti & Klontza (2008)
Colour				
Microplastics	Polychlorinated biphenyls, Polyaromatic hydrocarbons	Black or any dark colour	Increased	Frias *et al.* (2013), Antunes *et al.* (2013)
Density				
Microplastics	Chemicals	Low density High density	Increased Decreased	Lee *et al.* (2018), Fries & Zarfl (2012), Karapanagioti & Klontza (2008)

coefficient in low-density polyethylene, resulting in higher sorption of contaminants over low-density polyethylene compared to high-density polyethylene (Mato *et al.* 2001, 2002; Teuten *et al.* 2007; Karapanagioti & Klontza 2008; Fries & Zarfl 2012; Lee *et al.* 2018). This is so because high-density polyethylene has minimal branching compared to low-density polyethylene making it more rigid and less permeable leading to low diffusion of contaminants (Saleem *et al.* 1989). It is also reported that dark-coloured microplastic particles tend to sorb more contaminants compared to their uncoloured counterparts (Antunes *et al.* 2013). This is because of the fact that dark coloured microplastics contain higher amount of additives, such as polyurethane, which promote sorption (Wang *et al.* 2018). The cellular membrane-like structure of these additives helps the contaminating molecules to penetrate deeper inside the polymeric substance, thus making it possible for them to be carried away along with the microplastics (Dmitrienko & Zolotov 2002).

Ageing is another important parameter that affects the contaminant transport ability of the microplastics (Table 3). Ageing of the microplastics results in various oxidation processes that alter the composition as well as the structure of the particles in terms of crystal structure, size, exposed surface area, etc. (Wu *et al.* 2020). Sorption isotherms of various contaminants over microplastic particles have shown that crystal structure gets disturbed upon ageing, resulting in a more non-crystalline domain, which requires very low energy to disturb the polymer chain to adsorb the contaminants (Liu *et al.* 2019). The hydrogen bond among oxygen-containing functional groups is an important interaction, which could be generated on the surface of microplastics during the ageing process; hence, the sorption capacity of aged microplastics is found to be significantly higher than that of the virgin material (Yu *et al.* 2019). It has also been shown that aged fragments accumulate metals to a greater extent without reaching equilibrium, while virgin plastics attain equilibrium at a faster rate, thus accumulating less

(Brennecke *et al.* 2016). Overall, ageing has been found to enhance the contaminant transport capacity of the microplastics (Antunes *et al.* 2013). In contradiction to this, Muller *et al.* reported that ageing does not play any role in the sorption process of polypropylene (semi-crystalline), while in the case of polystyrene (amorphous) ageing results in low sorption of BTEX (benzene, toluene, ethylbenzene, and xylene) (Muller *et al.* 2018). The reason for low sorption of BTEX onto the aged polystyrene is reported to be the formation of an oxidized surface layer which increases surface polarity and thus, reduces the sorption of non-polar BTEX. Therefore, different microplastics may behave differently upon ageing, and chemical composition of the contaminants as well as that of the microplastics themselves plays an important role in this.

MICROPLASTICS IN DRINKING WATER: IMPLICATIONS FOR HUMAN HEALTH

Owing to the ubiquitous presence of microplastics, their entry into human beings and the consequent impact on health are inevitable. Microplastic ingestion in human may take place through contaminated drinking water (Kosuth *et al.* 2018), along with many other routes, for example, eating/drinking food items (Kosuth *et al.* 2018; Conti *et al.* 2020), seafood (Smith *et al.* 2018), honey and sugar (Liebezeit & Liebezeit 2013), commercially available common salt (Peixoto *et al.* 2019), and other plastic-wrapped food items (Rist *et al.* 2018). After ingestion, some of these particles may get excreted from human body *via* urine, bile, or faeces and with other metabolic functions due to their resistance to degradation (Wright & Kelly 2017). The rate of elimination of microplastics from the body is affected by the shape, size, polymer type, and additive chemicals associated with the ingested microplastics (Lusher *et al.* 2017). However, these particles also have the potential for bioaccumulation, especially with cumulative/chronic exposure, in secondary organs (Smith *et al.* 2018) after translocation from the gut. Owing to this bioaccumulation process, microplastics may prove to be harmful because of their inherent tendency of causing tissue obstruction (Peda *et al.* 2016). It has been shown that polystyrene microplastics do accumulate in the kidney, lungs, and intestine of mice resulting in oxidative stress, changes in lipid and energy metabolism, and neurotoxicity (Deng *et al.* 2017). Moreover, circulating microplastics have been shown to induce pulmonary hypertension and vascular dysfunction in *in-vivo* animal studies (Prata *et al.* 2020).

Research has also shown that ingested microplastic particles translocate out of the intestine through adsorption of particles adherent to mucus by specialized M-cells found over Peyer's patches (intestinal lymphoid tissue) (Ensign *et al.* 2012) or even *via* paracellular transfer through the single layer of the intestinal epithelium (persorption) (Prata *et al.* 2020). Microplastics (>700 nm) have been reported in human blood samples, which indicates the bioavailability of plastic particles in the human bloodstream (Leslie *et al.* 2022). Upon reaching the circulatory/lymphatic system, the microplastics are then carried to distant organ systems (Smith *et al.* 2018). It is important here to note that small microplastics owing to their large surface area do have higher potential for acting as adsorbate for contaminants and also for reaching up to the distant organs; thus posing comparatively serious health effects. Moreover, adsorption of plastic particles may also take place along with the large proteins in the body, which may induce alterations in the immune system (Powell *et al.* 2007; Sana *et al.* 2020).

The effect of microplastics on human health varies according to exposure characteristics and host susceptibility (Smith *et al.* 2018). Microplastic toxicity has mostly been studied for inhaled particles. The transport and effect of microplastic particles following ingestion has not been extensively studied (WHO 2019). Preliminary research has demonstrated several mechanisms of microplastic effect on human health such as exaggerated inflammatory response, genotoxicity, and oxidative stress resulting in cell and tissue damage, fibrosis, and potentially carcinogenesis (Deng *et al.* 2017; Schirinzi *et al.* 2017). Organ specific toxicity has been reported in the gastro-intestinal system, liver, reproductive system, and neurological system (Chang *et al.* 2020; Rai *et al.* 2021). Effect of microplastics on distant human organ systems ranges from an increased incidence of immune or neurodegenerative diseases (Prata *et al.* 2020), increased risk of lung diseases (Dong *et al.* 2020b), impairment in renal function (Monti *et al.* 2015) to bone loss secondary to an unopposed increase in the activity of osteoclasts responsible for bone reabsorption (Ormsby *et al.* 2016). It is also known that polyvinyl chloride is a proven carcinogen and causes angiosarcoma of the liver (Bolt 2005; Gennaro *et al.* 2008). Studies have further shown that microplastic particles can potentially cross the placental barrier as well, which may pose serious consequences on embryo development (Grafmueller *et al.* 2015; Ragusa *et al.* 2021).

Apart from the microplastics themselves, chemical additives and contaminants sorbed on to these particles might also pose serious health hazards (Ziccardi *et al.* 2016; Barboza *et al.* 2018; Rist *et al.* 2018). It has been reported in marine organisms that translocation of contaminants adsorbed on the microplastics into other body tissues increases with the duration of passage through the gut of the organisms (Chua *et al.* 2014). Similar may be the fate of microplastics in the human body as well. Moreover,

the chemicals/additives used in the manufacturing process of plastics/microplastics cause various impacts upon ingestion, such as reproductive abnormalities (Swan *et al.* 2005; Lang *et al.* 2008; Swan 2008). It has been demonstrated that chemicals, such as phthalates and bisphenol A (BPA), which are commonly added in microplastics, are found in the human body (Thompson *et al.* 2009). Moreover, epidemiological studies have proven the relation between phthalate levels and adverse human health effects (Swan *et al.* 2005). Microplastics are also known to adsorb various metals/metalloids, such as cadmium, manganese, lead, arsenic, copper, zinc, chromium, etc., on their surfaces (Brennecke *et al.* 2016; Gao *et al.* 2019; Selvam *et al.* 2021). Polyethylene terephthalate particles have been reported to accumulate lead, cadmium, and zinc (Abbasi *et al.* 2020). Likewise, arsenic, cadmium, chromium, and lead were found to be associated with high density polyethylene (Holmes *et al.* 2012; Jinhui *et al.* 2019; Mohsen *et al.* 2019). Deleterious health impacts associated with metals are widely recognized (Table 4) (Khan *et al.* 2008; Rehman *et al.* 2017; Jain *et al.* 2018; Jain *et al.* 2019) and altered endocrine system and abrupt hormonal responses have been reported in organisms due to the effects of microplastics laden with metals/metalloids (Rochman *et al.* 2014). Furthermore, ingested microplastics can also serve as vectors of harmful bacteria that are adsorbed on their surface such as *Vibrio* spp. (Kirstein *et al.* 2016). Microplastics carry and release their microbial load inside the human body and thus, can potentially lead to disruption of gut microbiome, infections, and various other adverse health effects (Prata *et al.* 2020). A detailed information on the impacts of microplastics on human health is provided by Wright & Kelly (2017), Barboza *et al.* (2018), Rist *et al.* (2018). Summary of various human health effects of microplastics is given in Table 4.

MICROPLASTICS: REMOVAL METHODS IN DRINKING WATER SUPPLIES

Microplastics removal in water/wastewater/sewage treatment plants is of necessary concern, as these are one of the major sources of microplastics in drinking water supply chain (Okoffo *et al.* 2019). Though there are a variety of treatment options

Table 4 | Human health aspects of microplastics

Type of microplastic	Particles/Chemical(s) associated	Effects on human body due to the microplastics' and/or associated chemicals	References
Polyethylene terephthalate	Lead, cadmium, and zinc	Cardiovascular effects, hypertension, reproductive issues, anaemia	Abbasi *et al.* (2020)
High density polyethylene	Arsenic, cadmium, chromium, and lead	Increased risk of dermal, renal, pulmonary cancer, cardiovascular effects, hypertension	Jinhui *et al.* (2019), Mohsen *et al.* (2019), Holmes *et al.* (2012)
Polycarbonate plastics, epoxy resins	Bisphenol A (BPA)	Adversely affects brain development leading to loss of sex differentiation in brain structures and behaviour, Suspected endocrine disrupting chemical	Rist *et al.* (2018), Talsness *et al.* (2009)
Polystyrene for Styrofoam packaging	Styrene	Endocrine disrupting chemical	Rist *et al.* (2018)
Polyethylene and polystyrene particles	–	Genotoxicity, apoptosis, and necrosis, leading to tissue damage, fibrosis, and carcinogenesis	Wright & Kelly (2017)
Polyethylene and polystyrene microparticles	–	Cytotoxicity due to microparticles (polyethylene 3–16 μm; polystyrene 10 μm) at cell level due to oxidative stress in cerebral and epithelial human cell lines	Schirinzi *et al.* (2017)
Polyvinyl chloride	Vinyl chloride	Angiosarcoma of liver	Gennaro *et al.* (2008), Bolt (2005)
Polystyrene	–	Fast movement of particles (<100 nm) through endothelium in bone marrow and uptake by phagocytizing cells	Oberdorster *et al.* (2006)
Polyvinyl chloride (in medical tubing)	Di(2-ethylhexyl) phthalate (DEHP)	High levels of BPA in infants	Green *et al.* (2005)
Polystyrene particles	–	Inflammatory effects due to the small size (<100 nm)	Brown *et al.* (2001)
Polyethylene particles	–	Particles up to 50 μm reported in lymph nodes, liver, and spleen, causing immune activation of macrophages and production of cytokines	Urban *et al.* (2000), Doorn *et al.* (1996), Hicks *et al.* (1996)

for various contaminants, microplastic-targeted treatment technologies are still in the nascent stage. It has been reported that microplastic concentration can be significantly reduced by ultrafiltration and reverse osmosis (Ziajahromi *et al.* 2017). In the conventional water treatment technology, primary and secondary treatment processes help in the removal of microplastics to a certain extent (Ma *et al.* 2019; Sun *et al.* 2019). The removal efficiency in wastewater treatment plants is calculated based upon the particle concentration of microplastics (*viz*. number of microplastic particles/litre) in the influent and effluent. As reported, approximately 50–98% of microplastics could be removed during primary treatment and 0.2–14% during secondary treatment (Sun *et al.* 2019). A membrane bioreactor is another option that directly treats the primary effluent. Talvitie *et al.* compared the microplastics' removal efficiency in terms of particle concentration before and after the application of different tertiary treatment processes and reported that the membrane bioreactor had the highest removal efficiency (99.9%), followed by rapid sand filtration (97%), and dissolved air floatation (95%) (Talvitie *et al.* 2017). However, even after the tertiary treatment, a significant fraction of microplastics remains in the water, having a size range of 20–100 μm and 100–190 μm (Ziajahromi *et al.* 2017; Sun *et al.* 2019). A combination of secondary and tertiary treatment processes has also been useful in the removal of microplastics. Wang *et al.* reported the microplastics' removal of approximately 61% using the sedimentation and coagulation techniques combined with the granular activated carbon (GAC) filtration (Wang *et al.* 2020b). Biochar-based filters have also been reported, which are able to remove microplastic particles of size up to 10 μm diameter (Wang *et al.* 2020c). As the impacts pertaining to the specific concentration and size range of microplastics re under research and anything specific is tough to say at present, research on the other technologies for removal of microplastics is needed.

Modification in various operational parameters of the existing water treatment technologies is another viable solution for microplastics removal. Ma *et al.* investigated the removal of polyethylene using aluminium and iron-based salts ($AlCl_3{\cdot}6H_2O$ and $FeCl_3{\cdot}6H_2O$, respectively) and reported that aluminium-based salts perform better compared to the iron-based salts, (Ma *et al.* 2019). It was also found that small particle size of plastics resulted in a higher removal rate owing to a larger surface area, which gets easily captured and removed by flocs. It was observed that the ionic strength and turbidity of water did not influence the removal efficiency (Ma *et al.* 2019).

As far as microplastics-targeted treatment technologies are concerned, a gravity-powered filtration system was designed to be used in the secondary effluent in wastewater treatment plants (Beljanski *et al.* 2016). However, this system is yet to be tested for real wastewater. Microplastics removal through dynamic membranes has also been tested at the lab-scale (Li *et al.* 2018b). These membranes were formed on a 90 μm mesh and operated under gravity; however, the feasibility of using these modalities at large scale is questionable, considering the high operational and construction cost involved. Moreover, a detailed review on the removal techniques of microplastics from water is provided by Padervand *et al.* (2020) and Singh *et al.* (2021).

Considering these findings, it can be said that the microplastics-targeted treatment technologies need to be explored further. Besides improvements in the wastewater treatment plant technologies, other simple and effective mechanisms also need to be developed. In this context, advancement in end-use treatment options, such as efficient filtration, may prove to be advantageous. Such systems should be made to remove microplastic particles on their own without combining with any other treatment method. Research is also needed to target the removal of specific size ranges of microplastics as small size particles (submicro- and nano-range) are known to penetrate deep into the body tissues. Moreover, minimization of the microplastics' production is the key issue. In this, enforcement of strict regulation and safe disposal of plastic products is of priority concern (Cheung & Fok 2017).

MICROPLASTICS: REGULATORY ACTIONS

Considering the seriousness of the issue of microplastic pollution, stringent actions on the global level are highly solicited. Sometimes, bioplastics are referred to as an alternative of conventional plastics considering their biodegradable properties (Hoffman *et al.* 2019). However, there are enough evidences to support that bioplastics do instigate a variety of risks for humans as well as other biotic species (Shruti & Muniasamy 2019). Therefore, regulations should be for the production, use, and safe disposal of microplastic particles. Though specific targeted actions are yet to be taken, various guidelines and initiatives have come up with an intent to curb and/or regulate microplastics pollution. Most of these initiatives have focussed on the minimization of production and use of (primary) microplastics, which will ultimately reduce the burden of microplastics in the environmental matrices and consequently in drinking water sources. Based on the Millennium Development Goals, United Nations General Assembly has targeted the sound management of various chemicals and other wastes with a focus on reducing their release to various environmental compartments (air/water/soil) for minimizing their effects on

health as well as environment (UN 2015). The world's major seven developed countries (G7) in 2015 discussed alternatives for plastic pollution (G7 2015) and currently are in the process of developing an action plan to tackle marine waste including plastic waste. REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulation for controlling the use of various chemicals has been propounded by the European Union (EU) in 2006 (REACH 2006). It addresses the issues of plastic monomers and associated additives. Recently, the European Chemical Agency (ECHA) proposed varied restrictions on the use of microplastics in products available in the EU market, so that their release into the environment may be minimized (ECHA 2019). In absolute terms, the proposal asks for reducing the release of 500,000 tonnes of microplastics over 20 years.

Various other governmental agencies and industrial sectors have also come forward and adopted new guidelines to combat pollution due to microplastics. In 2012, one of the leading consumer goods company – Unilever declared to phase out microplastics by 2015 from their personal care products, such as soap, skin scrubs, shower gel, etc. (Unilever 2012). Similarly, other brands such as Johnson and Johnson, Procter & Gamble, L'oreal, Colgate-Palmolive, etc. have also decided to ban the use of microplastics in their products (Fauna & Flora 2018). To take things forward, many nations have either proposed a new set of rules or amended the existing ones to restrict the use of microplastics. For example, the United States has promulgated the Microbead-free Waters Act in 2015, which prohibits the use of plastic particles in the manufacture of various rinse-off cosmetics products such as shampoos, soaps, toothpastes, etc. (McDevitt *et al.* 2017; US FDA 2017). Similarly, Canada, France, New Zealand, the United Kingdom, and many others have proposed regulations for curtailing the production and use of microplastics. A summary of various global/national initiatives is shown in Table 5.

Though concerted actions are being taken at various forums, there is still a state of confusion due to the wide variations in the type of microplastics found. Specifically, a major obstacle in setting a widely applicable regulation is the lack of a universal definition of microplastics. As of now, for the sake of simplicity, any solid polymeric, non-biodegradable content having a size <5 mm is considered as microplastic (Arthur *et al.* 2009; Thompson *et al.* 2009). However, there are various issues of contradiction, for example, the small plastic particles produced in the tyre abrasion process are not considered as microplastics as per the current norms (Verschoor 2015; Brennholt *et al.* 2018). Moreover, there is no consensus on what should be the lower size limit for microplastics. These limits will have an impact on the actual measurement of the amount of microplastics, which is certainly a fundamental requirement for regulation purposes.

CONCLUSION AND WAY FORWARD

It is noteworthy that research on microplastics and their impact on human health is in its initial stages but still there is sufficient evidence to substantiate the enormous risks posed by these tiny particles to the environment and human health. Apart from the inhalation and ingestion of microplastics through contaminated air and food, drinking water is one of the major routes to microplastic intake. As microplastics are laden with variety of other contaminants as well, it is necessary to keep in mind the environmental as well as physico-chemical factors affecting their contaminant transport capabilities, while developing new treatment options. Though various technologies are under way to achieve microplastics' removal from water treatment plants and the drinking water supply chain; it is better to restrict the manufacture and use of microplastics itself considering their harmful impacts posed through the intake of contaminated water and food.

Also, to understand the complete picture of the impacts of microplastics, thorough research is inevitable. As of now, most of the known adverse human health impacts caused by the microplastics are with respect to the inhaled route of exposure, while the understanding about the impacts due to the ingested route of exposure is scanty. There are several knowledge gaps in this area as well that needs to be worked upon. For example, the bio-accumulative potential of microplastics in human body is yet to be fully explored. Toxicological details such as lethal concentration and effective concentration limits also need to be defined. The impact of biofilms, pigments, microbes, and various other chemical moieties accumulated over microplastic particles also needs to be understood. Besides the scientific approach towards the reduction of these emerging contaminants, the regulatory approach needs to be targeted as well. As far as third world countries are concerned, these are still struggling to provide microbe-free safe water to their citizens; dealing with the microplastics in water might not be their priority in resource allocation. Hence, there is a need for development of a global action framework and technical as well as financial support from developed countries and multinational agencies to sensitize and combat microplastic pollution in developing countries. Though, remarkable attempts are being made to reduce the production and use of primary microplastics, it is necessary to acknowledge the fact that a significant portion of the pollution comes from the secondary sources after breakdown through

Table 5 | Global actions for the regulation of microplastics (Adapted from Kentin & Kaarto 2018)

Country	Regulation	Product category	Definition of microplastics
Canada (in force)	Microbeads in Toiletries Regulations (*Canada Gazette*, Part II: Vol. 151, No. 12, 2017)	Toiletries, meaning any personal hair, skin, teeth, or mouth care products for cleansing or hygiene, including exfoliants	Microbead: plastic microbeads that are ≤5 mm in size, any plastic particle, including different forms such as solid, hollow, amorphous and solubilized.
France (in force)	Decree prohibiting the placing on the market of rinse-off cosmetic products for exfoliation or cleansing that contain solid plastic particles (Amendment CD1857, 2019)	Rinse-off cosmetic products for exfoliation or cleansing	Solid plastic particles, with the exception of particles of natural origin not liable to persist in, or release active chemical or biological ingredients into the environment or to affect animal food chains
Ireland (in force)	Microbeads (Prohibition) Act, 2019 (S.I. 52 of 2019)	Outlawed the sale, manufacture, import, and export of products containing microplastics	Solid particle which is water insoluble and size ranging from 5 mm–1 nm
New Zealand (in force)	Waste Minimization (Microbeads) Regulations, 2017 (Section 23(1)(b), 2017/291)	Wash-down cosmetic products, cleaning products	Microbead: a water-insoluble plastic particle that is less than 5 mm at its widest point
Sweden (in force)	Draft regulation prohibiting the placing on the market of rinse-off cosmetics that contain solid plastic particles which have been added for exfoliating, cleaning, or polishing purposes (Ordinance (1998:944), 4 – 4b)	Rinse-off cosmetics products	Solid particles of plastic which are 5 mm or less in size in any dimension and which are insoluble in water
United Kingdom (England, Wales, Scotland)	The Environmental Protection (Microbeads) Regulations, 2017/18 (2017 No. 1312)	Rinse-off personal care products	Microbead: any water-insoluble solid plastic particle of less than or equal to 5 mm in any dimension
United States (in force)	Microbead-free Waters Act, 2015 (Public Law 114–114, 114th Congress, Dec. 28, 2015)	Rinse-off cosmetics products	Microbead: any solid plastic particle that is less than 5 mm in size and is intended to be used to exfoliate or cleanse the human body or any part thereof.
Belgium (notified)	Draft Sector Agreement to support the replacement of microplastics in consumer products (Notification Number 2017/0465/ B' (2 October 2017)	–	–
China (notified)	'Opinions on further strengthening the clean-up of plastic pollution' which laid out the plan to ban the manufacture of daily chemical products containing plastic microbeads (NDRC [2020] No. 80)	Daily chemical products	–
India (notified in 2017, implementation since 2020)	Classification for cosmetic raw materials and adjuncts, Part 2: List of raw materials generally not recognized as safe for use in cosmetics (BIS IS 4707−2:2017)	Cosmetic products	Non-biodegradable polymeric microbeads

(*Continued.*)

Table 5 | Continued

Country	Regulation	Product category	Definition of microplastics
Italy (notified)	Draft technical regulation banning the marketing of non-biodegradable and non-compostable cotton buds and exfoliating rinse-off cosmetic products or detergents containing microplastics (Notification No. 2018/258/I)	Exfoliating rinse-off cosmetics products and detergents	Water insoluble solid plastic particles of 5 mm or less, referring to definition in Commission Decision EU 2017/1217 of 23 June 2017
Japan (notified in 2018)	Enacted a bill aimed at reducing the use of microplastics, contained in some cosmetics and other products	Cosmetic and other products	–
South Korea (notified in 2021)	Draft regulation on Safety Standards *etc.* of Cosmetics	Cleansing products, dental cleansing products	Microbead: less than or equal to 5 mm in size

abiotic and biotic means (secondary microplastics). Therefore, the target needs to be the overall management of plastic waste. The monitoring and periodic check-ups of microplastics in the surface water bodies and groundwater should be made an important component in various water quality monitoring programmes. Moreover, qualitative research involving the public health approach should also be encouraged for understanding the people's perceptions to formulate various policies.

FUNDING

The authors are thankful to the Indian Council of Medical Research (ICMR), New Delhi for the financial support (project grant number ICMR-NIREH/BPL/IMP-PJ-44/2021–22/469: Principal Investigator – Surya Singh, ICMR – NIREH, Bhopal).

CONFLICTS OF INTERESTS

The authors have no conflicts of interest to declare that are relevant to the content of this article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Abbasi, S., Moore, F., Keshavarzi, B., Hopke, P. K., Naidu, R., Rahman, M. M., Oleszczuk, P. & Karimi, J. 2020 PET – microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. *Science of the Total Environment* **744**, 140984. doi: 10.1016/j.scitotenv.2020.140984.

Amaral-Zettler, L. A., Zettler, E. R., Slikas, B., Boyd, G. D., Melvin, D. W., Morrall, C. E., Proskurowski, G. & Mincer, T. J. 2015 The biogeography of the plastisphere: implications for policy. *Frontiers in Ecology and the Environment* **13**, 541–546. doi:10.1890/150017.

Amrutha, K. & Warrier, A. K. 2020 The first report on the source-to-sink characterization of microplastic pollution from a riverine environment in tropical India. *Science of the Total Environment* **739**, 140377. doi: 10.1016/j.scitotenv.2020.140377.

Andrady, A. L. 2011 Microplastics in the marine environment. *Marine Pollution Bulletin* **62**, 1596–1605. doi: 10.1016/j.marpolbul.2011.05.030.

Andrady, A. L., Pegram, J. E. & Song, Y. 1993 Studies on enhanced degradable plastics. II. weathering of enhanced photodegradable polyethylenes under marine and freshwater floating exposure. *Journal of Environmental Polymer Degradation* **1**, 117–126. doi: 10.1007/BF01418205.

Antunes, J. C., Frias, J. G. L., Micaelo, A. C. & Sobral, P. 2013 Resin pellets from beaches of the Portuguese coast and adsorbed persistent organic pollutants. *Estuarine, Coastal and Shelf Science* **130**, 62–69. doi: 10.1016/j.ecss.2013.06.016.

Arthur, C., Baker, J. & Bamford, H. 2009 *Occurrence, effects, and fate of microplastic marine debris. Proceedings of the International Research Workshop on Microplastic Marine Debris, Sep. 9–11, 2008, NOAA Technical Memorandum NOS-OR&R-30.* Available from: https://marinedebris.noaa.gov/proceedings-international-research-workshop-microplastic-marine-debris (accessed 18 July 2020).

Ashwini, S. K. & Varghese, G. K. 2020 Environmental forensic analysis of the microplastics pollution at 'Nattika' Beach, Kerala Coast, India. *Environmental Forensics* **21**, 21–36. doi: 10.1080/15275922.2019.1693442.

Bakir, A., Rowland, S. J. & Thompson, R. C. 2014 Transport of persistent organic pollutants by microplastics in estuarine conditions. *Estuarine, Coastal and Shelf Science* **140**, 14–21. doi: 10.1016/j.ecss.2014.01.004.

Barbosa, F., Adeyemi, J. A., Bocato, M. Z., Comas, A. & Campiglia, A. 2020 A critical viewpoint on current issues, limitations, and future research needs on micro- and nanoplastics studies: from the detection to the toxicological assessment. *Environmental Research* **182**, 109089. doi: 10.1016/j.envres.2019.109089.

Barboza, L. G. A. & Gimenez, B. C. G. 2015 Microplastics in the marine environment: current trends and future perspectives. *Marine Pollution Bulletin* **97**, 5–12. doi: 10.1016/j.marpolbul.2015.06.008.

Barboza, L. G. A., Vethaak, A. D., Lavorante, B. R. B. O., Lundebye, A. K. & Guihermino, L. 2018 Marine microplastic debris: an emerging issue for food security, food safety, and human health. *Marine Pollution Bulletin* **133**, 336–348. doi: 10.1016/j.marpolbul.2018.05.047.

Beljanski, A., Cole, C., Fuxa, F., Setiawan, E. & Singh, H. 2016 Efficiency and effectiveness of a low-cost, self-cleaning microplastic filtering system for wastewater treatment plants. In *Proceedings of the National Conference Undergraduate Research (NCUR)*, North Carolina, USA. Available from: https://www.ncurproceedings.org/ojs/index.php/NCUR2016/article/download/2064/1021 (accessed 30 June 2020).

Bolt, H. M. 2005 Vinyl chloride – a classical industrial toxicant of new interest. *Critical Reviews in Toxicology* **35**, 307–323. doi: 10.1080/10408440490915975.

Brennecke, D., Duarte, B., Paiva, F., Cacador, I. & Canning-Clode, J. 2016 Microplastics as vector for heavy metal contamination from the marine environment. *Estuarine, Coastal and Shelf Science* **178**, 189–195. doi: 10.1016/j.ecss.2015.12.003.

Brennholt, N., Heβ, M. & Reifferscheid, G. 2018 Freshwater microplastics: challenges for regulation and management. In: *Freshwater Microplastics, The Handbook of Environmental Chemistry* (Wagner, M. & Lambert, S., eds). Springer, Cham, pp. 239–272. doi: 10.1007/978-3-319-61615-5_12.

Brewer, A., Dror, I. & Berkowitz, B. 2020 The mobility of plastic nanoparticles in aqueous and soil environments: a critical review. *ACS Environmental Science and Technology Water* **1**, 48–57. doi: 10.1021/acsestwater.0c00130.

Brown, D. M., Wilson, M. R., MacNee, W., Stone, V. & Donaldson, K. 2001 Size-dependent proinflammatory effects of ultrafine polystyrene particles: a role for surface area and oxidative stress in the enhanced activity of ultrafines. *Toxicology and Applied Pharmacology* **175**, 191–199. doi: 10.1006/taap.2001.9240.

Carbery, M., O'Connor, W. & Thavamani, P. 2018 Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. *Environmental International* **115**, 400–409. doi: 10.1016/j.envint.2018.03.007.

Carpenter, E. J. & Smith, K. L. 1972 Plastics on the Sargasso Sea surface. *Science* **175**, 1240–1241. doi: 10.1126/science.175.4027.1240.

Carpenter, E. J., Anderson, S. J., Harvey, G. R., Miklas, H. P. & Peck, B. B. 1972 Polystyrene spherules in coastal waters. *Science* **178**, 749–750. doi: 10.1126/science.178.4062.749.

Chang, X., Xue, Y., Li, J., Zou, L. & Tang, M. 2020 Potential health impact of environmental micro- and nanoplastics pollution. *Journal of Applied Toxicology* **40**, 4–15. doi: 10.1002/jat.3915.

Cheung, P. K. & Fok, L. 2017 Characterization of plastic microbeads in facial scrubs and their estimated emissions in Mainland China. *Water Research* **122**, 53–61. doi: 10.1016/j.watres.2017.05.053.

Chua, E. M., Shimeta, J., Nugegoda, D., Morrison, P. D. & Clarke, B. O. 2014 Assimilation of polybrominated diphenyl ethers from microplastics by the marine amphipod, *Allorchestes compressa*. *Environmental Science and Technology* **48**, 8127–8134. doi: 10.1021/es405717z.

Conti, G. O., Ferrante, M., Banni, M., Favara, C., Nicolosi, I., Cristaldi, A., Fiore, M. & Zuccarello, P. 2020 Micro- and nano-plastics in edible fruits and vegetables. The first diet risks assessment for the general population. *Environmental Research* **187**, 109677. doi: 10.1016/j.envres.2020.109677.

Cox, L., Velarde, P., Cabrera, A., Hermosin, M. C. & Cornejo, J. 2007 Dissolved organic carbon interactions with sorption and leaching of diuron in organic – amended soils. *European Journal of Soil Science* **58**, 714–721. doi: 10.1111/j.1365-2389.2006.00856.x.

Deng, Y., Zhang, Y., Lemos, B. & Ren, H. 2017 Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. *Scientific Reports* **7**, 46687. doi: 10.1038/srep46687.

Dmitrienko, S. G. & Zolotov, Y. A. 2002 Polyurethane foams in chemical analysis: sorption of various substances and its analytical applications. *Russian Chemical Reviews* **71**, 159–174. doi: 10.1070/RC2002v071n02ABEH000703.

Dong, Y., Gao, M., Song, Z. & Qiu, W. 2019 Adsorption mechanism of As(III) on polytetrafluoroethylene particles of different size. *Environmental Pollution* **254**, 112950. doi: 10.1016/j.envpol.2019.07.118.

Dong, Y., Gao, M., Song, Z. & Qiu, W. 2020a As(III) adsorption onto different-sized polystyrene microplastic particles and its mechanism. *Chemosphere* **239**, 124792. doi: 10.1016/j.chemosphere.2019.124792.

Dong, C. D., Chen, C. W., Chen, Y. C., Chen, H. H., Lee, J. S. & Lin, C. H. 2020b Polystyrene microplastic particles: *In vitro* pulmonary toxicity assessment. *Journal of Hazardous Materials* **385**, 121575. doi: 10.1016/j.jhazmat.2019.121575.

Doorn, P. F., Campbell, P. A. & Amstutz, H. C. 1996 Metal versus polyethylene wear particles in total hip replacements: a review. *Clinical Orthopaedics and Related Research* **329S**, S206–S216. doi: 10.1097/00003086-199608001-00018.

Duis, K. & Coors, A. 2016 Microplastics in the aquatic and terrestrial environment: sources (with a special focus on personal care products), fate and effects. *Environmental Science Europe* **28**, 2. doi: 10.1186/s12302-015-0069-y.

ECHA 2019 *Guidance for Monomers and Polymers, ECHA-12-G-02-EN*. European Chemicals Agency. Available from: https://echa.europa.eu/hot-topics/microplastics (accessed 21 July 2020).

Eerkes-Medrano, D., Leslie, H. A. & Quinn, B. 2019 Microplastics in drinking water: a review and assessment. *Current Opinion in Environmental Science & Health* **7**, 69–75. doi: 10.1016/j.coesh.2018.12.001.

Ensign, L. M., Cone, R. & Hanes, J. 2012 Oral drug delivery with polymeric nanoparticles: the gastrointestinal mucus barriers. *Advanced Drug Delivery Reviews* **64**, 557–570. doi: 10.1016/j.addr.2011.12.009.

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H. & Amato, S. 2013 Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Marine Pollution Bulletin* **77**, 177–182. doi: 10.1016/j.marpolbul.2013.10.007.

EU 2018 *Microplastics: Sources, Effects and Solutions*. Available from: https://www.europarl.europa.eu/news/en/headlines/society/20181116STO19217/microplastics-sources-effects-and-solutions (accessed 26 August 2020).

Fauna & Flora International 2018 *Developing and Implementing Bans on Microbeads – A Guide for Policymakers*. Available from: https://www.fauna-flora.org/approaches/science-innovation/developing-implementing-microbead-bans/ (accessed 28 July 2020).

Fischer, M. & Scholz-Bottcher, B. M. 2019 Microplastics analysis in environmental samples – recent pyrolysis-gas chromatography-mass spectrometry method improvements to increase the reliability of mass-related data. *Analytical Methods* **11**, 2489–2497. doi: 10.1039/C9AY00600A.

Fotopoulou, K. N. & Karapanagioti, H. K. 2012 Surface properties of beached plastic pellets. *Marine Environmental Research* **81**, 70–77. doi: 10.1016/j.marenvres.2012.08.010.

Fred-Ahmadu, O. H., Bhagwat, G., Oluyoye, I., Benson, N. U., Ayejuyo, O. O. & Palanisami, T. 2020 Interaction of chemical contaminants with microplastics: principles and perspectives. *Science of the Total Environment* **706**, 135978. doi: 10.1016/j.scitotenv.2019.135978.

Fries, E. & Zarfl, C. 2012 Sorption of polycyclic aromatic hydrocarbons (PAHs) to low and high density polyethylene (PE). *Environmental Science and Pollution Research* **19**, 1296–1304. doi: 10.1007/s11356-011-0655-5.

Fries, E., Dekiff, J. H., Willmeyer, J., Nuelle, M. T., Ebert, M. & Remy, D. 2013 Identification of polymer types and additives in marine microscopic particles using pyrolysis – GC/MS and scanning electron microscopy. *Environmental Science: Processes and Impacts* **15**, 1949–1956. doi: 10.1039/C3EM00214D.

Frias, J. P. G. L., Antunes, J. C. & Sobral, P. 2013 Local marine litter survey – a case study in Alcobaca municipality. *Portugal Journal of Integrated Coastal Zone Management* **13**, 169–179. doi: 10.5894/rgci395.

Fuhrman, J. A., Steela, J. A., Hewson, I., Schwalbach, M. S., Brown, M. V., Green, J. L. & Brown, J. H. 2008 A latitudinal diversity gradient in planktonic marine bacteria. *Proceedings of National Academy of Sciences USA* **105**, 7774–7778. doi: 10.1073/pnas.0803070105.

Fuller, S. & Gautam, A. 2016 A procedure for measuring microplastics using pressurized fluid extraction. *Environmental Science and Technology* **50**, 5774–5780. doi: 10.1021/acs.est.6b00816.

Funck, M., Yildirim, A., Nickel, C., Schram, J., Schmidt, T. C. & Tuerk, J. 2020 Identification of microplastics in wastewater after cascade filtration using pyrolysis – GC-MS. *MethodsX* **7**, 100778. doi: 10.1016/j.mex.2019.100778.

G7 2015 Leaders' Declaration G7 Summit. 7-8 June 2015. SchlossElmau, Germany. pp. 17-18. Available from: https://sustainabledevelopment.un.org/content/documents/7320LEADERS%20STATEMENT_FINAL_CLEAN.pdf (accessed 31 August 2020).

Galloway, T. S. & Lewis, C. N. 2016 Marine microplastics spell big problems for future generations. *Proceedings of National Academy of Sciences USA* **113**, 2331–2333. doi: 10.1073/pnas.1600715113.

Gao, F., Li, J., Sun, C., Zhang, L., Jiang, F., Cao, W. & Zheng, L. 2019 Study on the capability and characteristics of heavy metals enriched on microplastics in marine environment. *Marine Pollution Bulletin* **144**, 61–67. doi: 10.1016/j.marpolbul.2019.04.039.

Garside, M. 2019 *Global Plastic Production Statistics*. Available from: https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/ (accessed 30 March 2020).

Gennaro, V., Ceppi, M., Crosignani, P. & Montanaro, F. 2008 Re-analysis of updated mortality among vinyl and polyvinyl chloride workers: confirmation of historical evidence and new findings. *BMC Public Health* **8**, 21. doi: 10.1186/1471-2458-8-21.

Geyer, R., Jambeck, J. R. & Law, K. L. 2017 Production, use, and fate of all plastics ever made. *Science Advances* **3**, e1700782. doi: 10.1126/sciadv.1700782.

Goedecke, C., Mulow-Stollin, U., Hering, S., Richter, J., Piechotta, C., Paul, A. & Braun, U. 2017 A first pilot study on the sorption of environmental pollutants on various microplastic materials. *Journal of Environmental Analytical Chemistry* **4**, 1–8. doi: 10.4172/2380-2391.1000191.

Grafmueller, S., Manser, P., Diener, L., Diener, P. A., Maeder-Althaus, X., Maurizi, L., Jochum, W., Krug, H. F., Bureki-Thurnherr, T., Mandach, U. V. & Wick, P. 2015 Bidirectional transfer study of polystyrene nanoparticles across the placental barrier in an *ex vivo* human placental perfusion model. *Environmental Health Perspectives* **123**, 1280–1286. doi: 10.1289/ehp.1409271.

Green, R., Hauser, R., Calafat, A. M., Weuve, J., Schettler, T., Ringer, S., Huttner, K. & Hu, H. 2005 Use of di(2-ethylhexyl) phthalate – containing medical products and urinary levels of mono(2-ethylhexyl) phthalate in neonatal intensive care unit infants. *Environmental Health Perspectives* **113**, 1222–1225. doi: 10.1289/ehp.7932.

Guo, X., Pang, J., Chen, S. & Jia, H. 2018 Sorption properties of tylosin on four different microplastics. *Chemosphere* **209**, 240–245. doi: 10.1016/j.chemosphere.2018.06.100.

Gusso, A. & Burnham, N. A. 2016 Investigation of the range of validity of the pairwise summation method applied to the calculation of the surface roughness correction to the vander Waals force. *Surface Science* **651**, 28–40. doi: 10.1016/j.susc.2016.03.014.

Hall-Stoodley, L., Costerton, J. W. & Stoodley, P. 2004 Bacterial biofilms: from the natural environment to infectious diseases. *Nature Reviews Microbiology* **2**, 95–108. doi: 10.1038/nrmicro821.

Hanvey, J. S., Lewis, P. J., Lavers, J. L., Crosbie, N. D., Pozo, K. & Clarke, B. O. 2017 A review of analytical techniques for quantifying microplastics in sediments. *Analytical Methods* **9**, 1369–1383. doi: 10.1039/C6AY02707E.

Harrison, J. P., Schratzberger, M., Sapp, M. & Osborn, A. M. 2014 Rapid bacterial colonization of low-density polyethylene microplastics in coastal sediment microcosms. *BMC Microbiology* **14**, 232. doi: 10.1186/s12866-014-0232-4.

Hartmann, N. B., Rist, S., Bodin, J., Jensen, L. H. S., Schmidt, S. N., Mayer, P., Meibom, A. & Baun, A. 2017 Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota. *Integrated Environmental Assessment and Management* **13**, 488–493. doi: 10.1002/ieam.1904.

Hicks, D. G., Judkins, A. R., Sickel, J. Z., Rosier, R. N., Puzas, J. E. & Keefe, R. J. O. 1996 Granular histiocytosis of pelvic lymph nodes following total hip arthroplasty. The presence of wear debris, cytokine production, and immunologically activated macrophages. *Journal of Bone and Joint Surgery* **78-A**, 482–496. doi: 10.2106/00004623-199604000-00002.

Hoffman, L. D., Ashworth, P., Laycock, B., Pratt, S. & Lant, P. 2019 Public attitudes towards bioplastics – knowledge, perception, and end-of-life management. *Resource Conservation and Recycling* **151**, 104479. doi: 10.1016/j.resconrec.2019.104479.

Holmes, L. A., Turner, A. & Thompson, R. C. 2012 Adsorption of trace metals to plastic resin pellets in the marine environment. *Environmental Pollution* **160**, 42–48. doi: 10.1016/j.envpol.2011.08.052.

Holmes, L. A., Turner, A. & Thompson, R. C. 2014 Interactions between trace metals and plastic production pellets under estuarine conditions. *Marine Chemistry* **167**, 25–32. doi: 10.1016/j.marchem.2014.06.001.

Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E. & Svendsen, C. 2017 Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment* **586**, 127–141. doi: 10.1016/j.scitotenv.2017.01.190.

Hu, J. Q., Yang, S. Z., Guo, L., Xu, X., Yao, T. & Xie, F. 2017 Microscopic investigation on the adsorption of lubrication oil on microplastics. *Journal of Molecular Liquids* **227**, 351–355. doi: 10.1016/j.molliq.2016.12.043.

Hu, E., Shang, S., Fu, Z., Zhao, X., Nan, X., Du, Y. & Chen, X. 2020 Cotransport of naphthalene with polystyrene nanoplastics (PSNP) in saturated porous media: effects of PSNP/naphthalene ratio and ionic strength. *Chemosphere* **245**, 125602. doi: 10.1016/j.chemosphere.2019.125602.

Huffer, T. & Hofmann, T. 2016 Sorption of non-polar organic compounds by micro-sized plastic particles in aqueous solution. *Environmental Pollution* **214**, 194–201. doi: 10.1016/j.envpol.2016.04.018.

Huffer, T., Weniger, A. K. & Hofmann, T. 2018 Sorption of organic compounds by aged polystyrene microplastic particles. *Environmental Pollution* **236**, 218–225. doi: 10.1016/j.envpol.2018.01.022.

Ilani, T., Schulz, E. & Chefetz, B. 2005 Interactions of organic compounds with wastewater dissolved organic matter. *Journal of Environmental Quality* **34**, 552–562. doi: 10.2134/jeq2005.0552.

Jain, C. K., Sharma, S. K. & Singh, S. 2018 Physico-chemical characteristics and hydrogeological mechanisms in groundwater with special reference to arsenic contamination in Barpeta District, Assam (India). *Environmental Monitoring and Assessment* **190**, 417. doi: 10.1007/s10661-018-6781-5.

Jain, C. K., Vaid, U., Sharma, S. K. & Singh, S. 2019 Assessment of potentially toxic elements' contamination in surface soils of Kulsi River Basin in North East India. *SN Applied Sciences* **1**, 673. doi: 10.1007/s42452-019-0689-8.

Jinhui, S., Sudong, X., Yan, N., Xia, P., Jiahao, Q. & Yongjian, X. 2019 Effects of microplastics and attached heavy metals on growth, immunity, and heavy metal accumulation in the yellow seahorse, *Hippocampus kuda* Bleeker. *Marine Pollution Bulletin* **149**, 110510. doi: 10.1016/j.marpolbul.2019.110510.

Johansen, M. P., Prentice, E., Cresswell, T. & Howell, N. 2018 Initial data on adsorption of Cs and Sr to the surfaces of microplastics with biofilm. *Journal of Environmental Radioactivity* **190-191**, 130–133. doi: 10.1016/j.jenvrad.2018.05.001.

Kalogerakis, N., Karkanorachaki, K., Kalogerakis, G. C., Triantafyllidi, E. I., Gotsis, A. D., Partsinevelos, P. & Fava, F. 2017 Microplastics generation: onset of fragmentation of polyethylene films in marine environment mesocosms. *Frontiers in Marine Sciences* **4**, 1–15. doi: 10.3389/fmars.2017.00084.

Karapanagioti, H. K. & Klontza, I. 2008 Testing phenanthrene distribution properties of virgin plastic pellets and plastic eroded pellets found on Lesvos island beaches (Greece). *Marine Environmental Pollution* **65**, 283–290. doi: 10.1016/j.marenvres.2007.11.005.

Karthik, R., Robin, R. S., Purvaja, R., Ganguly, D., Anandavelu, I., Raghuraman, R., Hariharan, G., Ramakrishna, A. & Ramesh, R. 2018 Microplastics along the beaches of southeast coast of India. *Science of the Total Environment* **645**, 1388–1399. doi: 10.1016/j.scitotenv.2018.07.242.

Kentin, E. & Kaarto, H. 2018 An EU ban on microplastics in cosmetic products and the right to regulate. review of European. *Comparative & International Environmental Law (RECIEL)* **27**, 254–266. doi: 10.1111/reel.12269.

Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z. & Zhu, Y. G. 2008 Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environmental Pollution* **152**, 686–692. doi: 10.1016/j.envpol.2007.06.056.

Kirstein, I. V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Loder, M. & Gerdts, G. 2016 Dangerous hitchhikers? evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. *Marine Environmental Research* **120**, 1–8. doi: 10.1016/j.marenvres.2016.07.004.

Koelmans, A. A., Nor, N. H. M., Hermsen, E., Kooi, M., Mintenig, S. M. & France, J. D. 2019 Microplastics in freshwaters and drinking water: critical review and assessment of data quality. *Water Research* **155**, 410–422. doi: 10.1016/j.watres.2019.02.054.

Kosuth, M., Mason, S. A. & Wattenberg, E. V. 2018 Anthropogenic contamination of tap water, beer, and sea salt. *PLOS One* **13**, e0194970. 1–18. doi: 10.1371/journal.pone.0194970.

Kwon, J. H., Chang, S., Hong, S. H. & Shim, W. J. 2017 Microplastics as a vector of hydrophobic contaminants: importance of hydrophobic additives. *Integrated Environmental Assessment and Management* **13**, 494–499. doi: 10.1002/ieam.1906.

Lang, I. A., Galloway, T. S., Scarlett, A., Henley, W. E., Depledge, M., Wallace, R. B. & Melzer, D. 2008 Association of urinary Bisphenol A concentration with medical disorders and laboratory abnormalities in adults. *Journal of American Medical Association* **300**, 1303–1310. doi: 10.1001/jama.300.11.1303.

Lebreton, L. C. M., Zwet, J. V., Damsteeg, J. W., Slat, B., Andrady, A. & Reisser, J. 2017 River plastic emissions to the world's oceans. *Nature Communications* **8**, 15611. 1–10. doi: 10.1038/ncomms15611.

Lee, H., Byun, D. E., Kim, J. M. & Kwon, J. H. 2018 Desorption modelling of hydrophobic organic chemicals from plastic sheets using experimentally determined diffusion coefficients in plastics. *Marine Pollution Bulletin* **126**, 312–317. doi: 10.1016/j.marpolbul.2017.11.032.

Lenz, R., Enders, K., Stedmon, C. A., Mackenzie, D. M. A. & Nielsen, T. G. 2015 A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. *Marine Pollution Bulletin* **100**, 82–91. doi: 10.1016/j.marpolbul.2015.09.026.

Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J. & Lamoree, M. H. 2022 Discovery and quantification of plastic particle pollution in human blood. *Environment International* 107199. In Press. doi: 10.1016/j.envint.2022.107199.

Li, J., Zhang, K. & Zhang, H. 2018a Adsorption of antibiotics on microplastics. *Environmental Pollution* **237**, 460–467. doi: 10.1016/j.envpol.2018.02.050.

Li, L., Xu, G., Yu, H. & Xing, J. 2018b Dynamic membrane for micro-particle removal in wastewater treatment: performance and influencing factors. *Science of the Total Environment* **627**, 332–340. doi: 10.1016/j.scitotenv.2018.01.239.

Li, Y., Li, M., Li, Z., Yang, L. & Liu, X. 2019 Effects of particle size and solution chemistry on Triclosan sorption on polystyrene microplastic. *Chemosphere* **231**, 308–314. doi: 10.1016/j.chemosphere.2019.05.116.

Liebezeit, G. & Liebezeit, E. 2013 Non-pollen particulates in honey and sugar. *Food Additives & Contaminants: Part A* **30**, 2136–2140. doi: 10.1080/19440049.2013.843025.

Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X. & He, D. 2018a Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. *Environmental Pollution* **242**, 855–862. doi:10.1016/j.envpol.2018.07.051.

Liu, X., Zheng, M., Wang, L., Ke, R., Lou, Y., Zhang, X., Dong, X. & Zhang, Y. 2018b Sorption behaviours of tris-(2,3-dibromopropyl) isocyanurate and hexabromocyclododecanes on polypropylene microplastics. *Marine Pollution Bulletin* **135**, 581–586. doi: 10.1016/j.marpolbul.2018.07.061.

Liu, G., Zhu, Z., Yang, Y., Sun, Y., Yu, F. & Ma, J. 2019 Sorption behaviour and mechanism of hydrophilic organic chemicals to virgin and aged microplastics in freshwater and sea water. *Environmental Pollution* **246**, 26–33. doi: 10.1016/j.envpol.2018.11.100.

Loder, M. G. J., Kuczera, M., Mintenig, S., Lorenz, C. & Gerdts, G. 2015 Focal plane array detector-based micro – Fourier transform infrared imaging for the analysis of microplastics in environmental samples. *Environmental Chemistry* **12**, 563–581. doi: 10.1071/EN14205.

Lusher, A., Hollman, P. & Mendoza-Hill, J. 2017 Microplastics in fisheries and aquaculture – Status of knowledge on their occurrence and implications for aquatic organisms and food safety. FAO Fisheries and Aquaculture Technical Paper 615. Available from: http://www.fao.org/3/a-i7677e.pdf (accessed 3 August 2020).

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. *Chemical Engineering Journal* **359**, 159–167. doi: 10.1016/j.cej.2018.11.155.

Magnusson, K. & Noren, F. 2014 Screening of microplastic particles in and downstream a wastewater treatment plant. IVL Swedish Environmental Research Institute. C55:1–22. Available from: https://www.diva-portal.org/smash/get/diva2:773505/FULLTEXT01.pdf (accessed 15 July 2020).

Mai, L., Bao, L. J., Shi, L., Wong, C. S. & Zeng, E. Y. 2018 A review of methods for measuring microplastics in aquatic environments. *Environmental Science and Pollution Research* **25**, 11319–11332. doi: 10.1007/s11356-018-1692-0.

Mason, S. A., Welch, V. G. & Neratko, J. 2018 Synthetic polymer contamination in bottled water. *Frontiers in Chemistry* **6**, 1–11. doi: 10.3389/fchem.2018.00407.

Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C. & Kaminuma, T. 2001 Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science and Technology* **35**, 318–324. doi: 10.1021/es0010498.

Mato, Y., Takada, H., Zakaria, M. P., Kuriyama, Y. & Kanehiro, H. 2002 Toxic chemicals contained in plastic resin pellets in the marine environment – spatial difference in pollutant concentrations and the effects of resin type. *Environmental Science* **15**, 415–423.

McCormick, A., Hoellein, T. J., Mason, S. A., Schluep, J. & Kelly, J. J. 2014 Microplastic is an abundant and distinct microbial habitat in an urban river. *Environmental Science and Technology* **48**, 11863–11871. doi: 10.1021/es503610r.

McDevitt, J. P., Criddle, C. S., Morse, M., Hale, R. C., Bott, C. B. & Rochman, C. M. 2017 Addressing the issue of microplastics in the wake of the microbead-free waters act – a new standard can facilitate improved policy. *Environmental Science and Technology* **51**, 6611–6617. doi: 10.1021/acs.est.6b05812.

Mintenig, S. M., Loder, M. G. J., Primpke, S. & Gerdts, G. 2019 Low numbers of microplastics detected in drinking water from ground water sources. *Science of the Total Environment* **648**, 631–635. doi: 10.1016/j.scitotenv.2018.08.178.

Mohsen, M., Wang, Q., Zhang, L., Sun, L., Lin, C. & Yang, H. 2019 Heavy metals in sediment, microplastic, and sea cucumber *Apostichopus japonicas* from farms in China. *Marine Pollution Bulletin* **143**, 2–49. doi: 10.1016/j.marpolbul.2019.04.025.

Monti, D. M., Guarnieri, D., Napolitano, G., Piccoli, R., Netti, P., Fusco, S. & Arciello, A. 2015 Biocompatibility, uptake, and endocytosis pathways of polystyrene nanoparticles in primary human renal epithelial cells. *Journal of Biotechnology* **193**, 3–10. doi: 10.1016/j.jbiotec.2014.11.004.

Muller, A., Becker, R., Dorgerloh, U., Simon, F. G. & Braun, U. 2018 The effect of polymer ageing on the uptake of fuel aromatics and ethers by microplastics. *Environmental Pollution* **240**, 639–646. doi: 10.1016/j.envpol.2018.04.127.

Ni, H. G., Lu, S. Y., Mo, T. & Zeng, H. 2016 Brominated flame retardant emissions from the open burning of five plastic wastes and implications for environmental exposure in China. *Environmental Pollution* **214**, 70–76. doi: 10.1016/j.envpol.2016.03.049.

Novotna, K., Cermakova, L., Pivokonska, L., Cajthaml, T. & Pivokonsky, M. 2019 Microplastics in drinking water treatment – current knowledge and research needs. *Science of the Total Environment* **667**, 730–740. doi: 10.1016/j.scitotenv.2019.02.431.

Oberbeckmann, S., Fuchs, B. M., Meiners, M., Wichels, A., Wiltshire, K. H. & Gerdts, G. 2012 Seasonal dynamics and modelling of a *Vibrio* community in coastal waters of the North Sea. *Microbial Ecology* **63**, 543–551. doi: 10.1007/s00248-011-9990-9.

Oberbeckmann, S., Loeder, M. G., Gerdts, G. & Osborn, A. M. 2014 Spatial and seasonal variation in diversity and structure of microbial biofims on marine plastics in Northern European Waters. *FEMS Microbiology Ecology* **90**, 478–492. doi: 10.1111/1574-6941.12409.

Oberbeckmann, S., Loder, M. G. J. & Labrenz, M. 2015 Marine microplastic – associated biofilms – a review. *Environmental Chemistry* **12**, 551–562. doi: 10.1071/EN15069.

Oberbeckmann, S., Kreikemeyer, B. & Labrenz, M. 2018 Environmental factors support the formation of specific bacterial assemblages on microplastics. *Frontiers in Microbiology* **8**, 2709. doi: 10.3389/fmicb.2017.02709.

Oberdorster, G., Oberdorster, E. & Oberdorster, J. 2006 Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles. *Environmental Health Perspectives* **31**, 823–839. doi: 10.1289/ehp.7339.

Okoffo, E. D., O'Brien, S., O'Brian, J. W., Tscharke, B. & Thomas, K. V. 2019 Wastewater treatment plants as a source of plastics in the environment: a review of occurrence, methods for identification, quantification and fate. *Environmental Science: Water Research and Technology* **5**, 1908–1931. doi: 10.1039/C9EW00428A.

Ormsby, R. T., Cantley, M., Kogawa, M., Soloman, B., Haynes, D. R., Findlay, D. M. & Atkins, G. J. 2016 Evidence that osteocyte perilacunar remodelling contributes to polyethylene wear particle induced osteolysis. *Acta Biomaterialia* **33**, 242–251. doi: 10.1016/j.actbio.2016.01.016.

Oßmann, B. E., Sarau, G., Holtmannspotter, H., Pischetsrieder, M., Christiansen, S. H. & Dicke, W. 2018 Small sized microplastics and pigmented particles in bottled mineral water. *Water Research* **141**, 307–316. doi: 10.1016/j.watres.2018.05.027.

Padervand, M., Lichtfouse, E., Robert, D. & Wang, C. 2020 Removal of microplastics from the environment: a review. *Environmental Chemistry Letters* **18**, 807–828. doi: 10.1007/s10311-020-00983-1.

Panno, S. V., Kelly, W. R., Scott, J., Zheng, W., McNeish, R. E., Holm, N., Hoellein, T. J. & Baranski, E. L. 2019 Microplastic contamination in Karst groundwater systems. *Groundwater* **57**, 189–196. doi: 10.1111/gwat.12862.

Peda, C., Caccamo, L., Fossi, M. C., Gai, F., Andaloro, F., Genovese, L., Perdichizzi, A., Romeo, T. & Maricchiolo, G. 2016 Intestinal alterations in European sea bass *Dicentrarchus labrax* (Linnaeus, 1758) exposed to microplastics: preliminary results. *Environmental Pollution* **212**, 251–256. doi: 10.1016/j.envpol.2016.01.083.

Pegram, J. E. & Andrady, A. L. 1989 Outdoor weathering of selected polymeric materials under marine exposure conditions. *Polymer Degradation and Stability* **26**, 333–345. doi: 10.1016/0141-3910(89)90112-2.

Peixoto, D., Pinheiro, C., Amorim, J., Oliva-Teles, L., Guilhermino, L. & Vieira, M. N. 2019 Microplastic pollution in commercial salt for human consumption: a review. *Estuarine, Coastal and Shelf Science* **219**, 161–168. doi: 10.1016/j.ecss.2019.02.018.

Peters, C. A., Hendrickson, E., Minor, E. C., Schreiner, K., Halbur, J. & Bratton, S. P. 2018 Pyr-GC/MS analysis of microplastics extracted from the stomach content of benthivore fish from the Texas Gulf Coast. *Marine Pollution Bulletin* **137**, 91–95. doi: 10.1016/j.marpolbul.2018.09.049.

Pivokonsky, M., Cermakova, L., Novotna, K., Peer, P., Cajthaml, T. & Janda, V. 2018 Occurrence of microplastics in raw and treated drinking water. *Science of the Total Environment* **643**, 1644–1651. doi: 10.1016/j.scitotenv.2018.08.102.

Plastics Europe 2019 *Plastics – The Facts 2019. An Analysis of European Plastics Production, Demand and Waste Data*. Plastics Europe, Brussels, Belgium. Available from: https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf (accessed 30 June 2020).

Powell, J. J., Thoree, V. & Pele, L. C. 2007 Dietary microparticles and their impact on tolerance and immune responsiveness of the gastrointestinal tract. *British Journal of Nutrition* **98**, S59–S63. doi: 10.1017/S0007114507832922.

Prata, J. C., Costa, J. P., Lopes, I., Duarte, A. C. & Santos, T. R. 2020 Environmental exposure to microplastics: an overview on possible human health effects. *Science of the Total Environment* **702**, 134455. doi: 10.1016/j.scitotenv.2019.134455.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M. C. A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M. & Giorgini, E. 2021 Plasticenta: first evidence of microplastics in human placenta. *Environmental International* **146**, 106274. doi: 10.1016/j.envint.2020.106274.

Rai, P. K., Lee, J., Brown, R. J. C. & Kim, K. H. 2021 Environmental fate, ecotoxicity biomarkers, and potential health effects of micro- and nano-scale plastic contamination. *Journal of Hazardous Materials* **403**, 123910. doi: 10.1016/j.jhazmat.2020.123910.

Rajmohan, K. V. S., Ramya, C., Viswanathan, M. R. & Varjani, S. 2019 Plastic pollutants: effective waste management for pollution control and abatement. *Current Opinions in Environmental Science and Health* **12**, 72–84. doi: 10.1016/j.coesh.2019.08.006.

REACH 2006 *Regulation (EC) No 1907/2006 – Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH)*. Available from: https://osha.europa.eu/en/legislation/directives/regulation-ec-no-1907-2006-of-the-european-parliament-and-of-the-council (accessed 28 August 2020).

Rehman, K., Fatima, F., Waheed, I. & Akash, M. S. H. 2017 Prevalence of exposure of heavy metals and their impact on health consequences. *Journal of Cellular Biochemistry* **119**, 157–184. doi: 10.1002/jcb.26234.

Rezania, S., Park, J., Md Din, M. F., Taib, S. M., Talaiekhozani, A., Yadav, K. K. & Kamyab, H. 2018 Microplastics pollution in different aquatic environments and biota: a review of recent studies. *Marine Pollution Bulletin* **133**, 191–208. doi: 10.1016/j.marpolbul.2018.05.022.

Rillig, M. C. 2012 Microplastic in terrestrial ecosystems and the soil? *Environmental Science and Technology* **46**, 6453–6454. doi: 10.1021/es302011r.

Rist, S., Almroth, B. C., Hartmann, N. B. & Karlsson, T. M. 2018 A critical perspective on early communications concerning human health aspects of microplastics. *Science of the Total Environment* **626**, 720–726. doi: 10.1016/j.scitotenv.2018.01.092.

Robin, R. S., Karthik, R., Purvaja, R., Ganguly, D., Anandavelu, I., Mugilarasan, M. & Ramesh, R. 2020 Holistic assessment of microplastics in various coastal environmental matrices, southwest coast of India. *Science of the Total Environment* **703**, 134947. doi: 10.1016/j.scitotenv.2019.134947.

Rochman, C. M., Manzano, C., Hentschel, B. T., Simonich, S. L. M. & Hoh, E. 2013 Polystyrene plastic: a source and sink for polycyclic aromatic hydrocarbons in the marine environment. *Environmental Science and Technology* **47**, 13976–13984. doi: 10.1021/es403605f.

Rochman, C. M., Kurobe, T., Flores, I. & Teh, S. J. 2014 Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without adsorbed chemical pollutants from the marine environment. *Science of the Total Environment* **493**, 656–661. doi: 10.1016/j.scitotenv.2014.06.051.

Rodrigues, M. O., Abrantes, N., Goncalves, F. J. M., Nogueira, H., Marques, J. C. & Goncalves, A. M. M. 2018 Spatial and temporal distribution of microplastics in water and sediments of a freshwater system (Antua River, Portugal). *Science of the Total Environment* **633**, 1549–1559. doi: 10.1016/j.scitotenv.2018.03.233.

Rodriguez-Seijo, A. & Pereira, R. 2018 Microplastics in agricultural soils. Are they a real environmental hazard? Chapter 3. In: *Bioremediation of Agricultural Soils*. CRC Press, Boca Raton, FL.

Saleem, M., Asfour, A. F. A., Kee, D. D. & Harrison, B. 1989 Diffusion of organic penetrants through low density polyethylene (LDPE) films: effect of size and shape of the penetrant molecules. *Journal of Applied Polymer Science* **37**, 617–625. doi: 10.1002/app.1989.070370303.

Salta, M., Wharton, J. A., Blache, Y., Stokes, K. R. & Briand, J. F. 2013 Marine biofilms on artificial surfaces: structure and dynamics. *Environmental Microbiology* **15**, 2879–2893. doi: 10.1111/1462-2920.12186.

Sana, S. S., Dogiparthi, L. K., Gangadhar, L., Chakravorty, A. & Abhishek, N. 2020 Effects of microplastics and nanoplastics on marine environment and human health. *Environmental Science and Pollution Research* **27**, 44743–44756. doi: 10.1007/s11356-020-10573-x.

Schirinzi, G. F., Perez-Pomeda, I., Sanchis, J., Rossini, C., Farre, M. & Barcelo, D. 2017 Cytotoxic effects of commonly used nanomaterials and microplastics on cerebral and epithelial human cells. *Environmental Research* **159**, 579–587. doi: 10.1016/j.envres.2017.08.043.

Schymanski, D., Goldbeck, C., Humpf, H. U. & Furst, P. 2018 Analysis of microplastics in water by micro-Raman spectroscopy: release of plastic particles from different packaging into mineral water. *Water Research* **129**, 154–162. doi: 10.1016/j.watres.2017.11.011.

Selvam, S., Jesuraja, K., Venkatramanan, S., Roy, P. D. & Kumari, V. J. 2021 Hazardous microplastic characteristics and its role as a vector of heavy metal in groundwater and surface water of coastal south India. *Journal of Hazardous Materials* **402**, 123786. doi: 10.1016/j.jhazmat.2020.123786.

Shruti, V. C. & Muniasamy, G. K. 2019 Bioplastics: missing link in the era of microplastics. *Science of the Total Environment* **697**, 134139. doi: 10.1016/j.scitotenv.2019.134139.

Silva, A. B., Bastos, A. S., Justino, C. I. L., da Costa, J. P., Durate, A. C. & Rocha-Santos, T. A. P. 2018 Microplastics in the environment: challenges in analytical chemistry – a review. *Analytica Chimica Acta* **1017**, 1–19. doi: 10.1016/j.aca.2018.02.043.

Sindiku, O., Babayemi, J. O., Tysklind, M., Osibanjo, O., Weber, R., Watson, A., Schlummer, M. & Lundstedt, S. 2015 Polybrominated dibenzo-*p*-dioxins and dibenzofurans (PBDD/Fs) in *e*-waste plastic in Nigeria. *Environmental Science and Pollution Research* **22**, 14515–14529. doi: 10.1007/s11356-015-5260-6.

Singh, S., Kalyanasundaram, M. & Diwan, V. 2021 Removal of microplastics from wastewater: available techniques and way forward. *Water Science & Technology*. **84**, 3689–3704. doi: 10.2166/wst.2021.472.

Smith, M., Love, D. C., Rochman, C. M. & Neff, R. A. 2018 Microplastics in seafood and the implications for human health. *Current Environmental Health Reports* **5**, 375–386. doi: 10.1007/s40572-018-0206-z.

Sun, J., Dai, X., Wang, Q., Loosdrecht, M. C. M. V. & Ni, B. J. 2019 Microplastics in wastewater treatment plants: detection, occurrence, and removal. *Water Research* **152**, 21–37. doi: 10.1016/j.watres.2018.12.050.

Swan, S. H. 2008 Environmental phthalate exposure in relation to reproductive outcomes and other health end-points in humans. *Environmental Research* **108**, 177–184. doi: 10.1016/j.envres.2008.08.007.

Swan, S. H., Main, K. M., Liu, F., Stewart, S. L., Kruse, R. L., Calafat, A. M., Mao, C. S., Redmon, J. B., Ternand, C. L., Sullivan, S. & Teague, J. L. & Study for future families research team 2005 Decrease in anogenital distance among male infants with prenatal phthalate exposure. *Environmental Health Perspectives* **113**, 1056–1061. doi: 10.1289/ehp.8100.

Takada, H. 2006 Call for pellets! International Pellet Watch Global Monitoring of POPs using beached resin pellets. *Marine Pollution Bulletin* **52**, 1547–1548. doi: 10.1016/j.marpolbul.2006.10.010.

Talsness, C. E., Andrade, A. J. M., Kuriyama, S. N., Taylor, J. A. & vomSaal, F. S. 2009 Components of plastic: experimental studies in animals and relevance for human health. *Philosophical Transactions of the Royal Society B* **364**, 2079–2096. doi: 10.1016/j.marpolbul.2006.10.010.

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

Tan, X., Yu, X., Cai, L., Wang, J. & Peng, J. 2019 Microplastics and associated PAHs in surface water from the Feilaixia Reservoir in the Beijiang River, China. *Chemosphere* **221**, 834–840. doi: 10.1016/j.chemosphere.2019.01.022.

Teuten, E. L., Rowland, S. J., Galloway, T. S. & Thompson, R. C. 2007 Potential for plastics to transport hydrophobic contaminants. *Environmental Science and Technology* **41**, 7759–7764. doi: 10.1021/es071737 s.

Thompson, R. C., Moore, C. J., vomSaal, F. S. & Swan, S. H. 2009 Plastics, the environment and human health: current consensus and future trends. *Philosophical Transactions of the Royal Society B* **364**, 2153–2166. doi: 10.1098/rstb.2009.0053.

Thornton, J., McCally, M., Orris, P. & Weinberg, J. 1996 Hospitals and plastics. Dioxin prevention and medical waste incinerators. *Public Health Reports* **111**, 298–313. PMID: 8711095.

Turner, A. & Holmes, L. A. 2015 Adsorption of trace metals by microscopic pellets in fresh water. *Environmental Chemistry* **12**, 600–610. doi: 10.1071/EN14143.

UN 2015 Transforming our world: the 2030 Agenda for Sustainable Development. Resolution No. A/RES/70/1 adopted by the General Assembly of the United Nations on 25 Sep. 2015. Available from: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf (accessed 13 August 2020).

Unilever 2012 *Unilever to Phase out 'Microplastics' by 2015*. Available from: https://phys.org/news/2012-12-unilever-phase-microplastics.html (accessed 10 July 2020).

Urban, R. M., Jacobs, J. J., Tomlinson, M. J., Gavrilovic, J., Black, J. & Peoch, M. 2000 Dissemination of wear particles to the liver, spleen, and abdominal lymph nodes of patients with hip or knee replacement. *The Journal of Bone& Joint Surgery* **82-A**, 457–477. doi: 10.2106/00004623-200004000-00002.

USFDA 2017 *The Microbead-Free Waters Act, U.S. Food and Drug Administration*. Available from: https://www.fda.gov/cosmetics/cosmetics-laws-regulations/microbead-free-waters-act-faqs (accessed 10 July 2020).

Velzeboer, I., Kwadijk, C. J. A. F. & Koelmans, A. A. 2014 Strong sorption of PCBs to nanoplastics, microplastics, carbon nanotubes, and fullerenes. *Environmental Science and Technology* **48**, 4869–4876. doi: 10.1021/es405721v.

Verschoor, A. J. 2015 *Towards A Definition of Microplastics. Considerations for the Specification of Physico-Chemical Properties. RIVM Letter Report 2015–0116*. Available from: https://www.rivm.nl/bibliotheek/rapporten/2015-0116.pdf (accessed 3 September 2020).

Virsek, M. K., Lovsin, M. N., Koren, S., Krzan, A. & Peterlin, M. 2017 Microplastics as a vector for the transport of the bacterial fish pathogen species *Aeromonas salmonicida*. *Marine Pollution Bulletin* **125**, 301–309. doi: 10.1016/j.marpolbul.2017.08.024.

Wagner, M. & Lambert, S. 2018 *Freshwater Microplastics: Emerging Environmental Contaminants? The Handbook of Environmental Chemistry*, Vol. 58. Springer Open. doi: 10.1007/978-3-319-61615-5.

Wang, W. & Wang, J. 2018 Different partition of polycyclic aromatic hydrocarbon on environmental particulates in freshwater: microplastics in comparison to natural sediment. *Ecotoxicology and Environmental Safety* **147**, 648–655. doi: 10.1016/j.ecoenv.2017.09.029.

Wang, F., Shih, K. M. & Li, X. Y. 2015 The partition behaviour of perfluorooctanesulfonate (PFOS) and perfluorooctanesulfonamide (FOSA) on microplastics. *Chemosphere* **119**, 841–847. doi: 10.1016/j.chemosphere.2014.08.047.

Wang, F., Wong, C. S., Chen, D., Lu, X., Wang, F. & Zeng, E. Y. 2018 Interaction of toxic chemicals with microplastics: a critical review. *Water Research* **139**, 208–219. doi: 10.1016/j.watres.2018.04.003.

Wang, T., Yu, C., Chu, Q., Wang, F., Lan, T. & Wang, J. 2020a Adsorption behaviour and mechanism of five pesticides on microplastics from agricultural polyethylene films. *Chemosphere* **244**, 125491. doi: 10.1016/j.chemosphere.2019.125491.

Wang, Z., Lin, T. & Chen, W. 2020b Occurrence and removal of microplastics in an advanced drinking water treatment plant (ADWTP). *Science of the Total Environment* **700**, 134520. doi: 10.1016/j.scitotenv.2019.134520.

Wang, Z., Sedighi, M. & Lea-Langton, A. 2020c Filtration of microplastic spheres by biochar: removal efficiency and immobilisation mechanisms. *Water Research* **184**, 116165. doi: 10.1016/j.watres.2020.116165.

Weinstein, J. E., Crocker, B. K. & Gray, A. D. 2016 From macroplastics to microplastics: degradation of high-density polyethylene, polypropylene, and polystyrene in a salt marsh habitat. *Environmental Toxicology and Chemistry* **35**, 1632–1640. doi: 10.1002/etc.3432.

WHO 2019 *Microplastics in Drinking Water*. World Health Organization report. Switzerland. Available from: https://apps.who.int/iris/bitstream/handle/10665/326499/9789241516198-eng.pdf?ua=1 (accessed 20 January 2021).

Wright, S. L. & Kelly, F. J. 2017 Plastic and human health: a micro issue? *Environmental Science and Technology* **51**, 6634–6647. doi: 10.1021/acs.est.7b00423.

Wu, C., Zhang, K., Huang, X. & Liu, J. 2016 Sorption of pharmaceuticals and personal care products to polyethylene debris. *Environmental Science and Pollution Research* **23**, 8819–8826. doi: 10.1007/s11356-016-6121-7.

Wu, X., Pan, J., Li, M., Li, Y., Bartlam, M. & Wang, Y. 2019 Selective enrichment of bacterial pathogens by microplastic biofilm. *Water Research* **165**, 114979. doi: 10.1016/j.watres.2019.114979.

Wu, X., Liu, P., Huang, H. & Gao, S. 2020 Adsorption of triclosan onto different aged polypropylene microplastics: critical effect of cations. *Science of the Total Environment* **717**, 137033. doi: 10.1016/j.scitotenv.2020.137033.

Xu, D., Zhou, X. & Wang, X. K. 2008 Adsorption and desorption of Ni^{+2} on namontmorillonite: effect of pH, ionic strength, fulvic acid, humic acid, and addition sequences. *Applied Clay Science* **39**, 133–141. doi: 10.1016/j.clay.2007.05.006.

Xu, P., Peng, G., Su, L., Gao, Y., Gao, L. & Li, D. 2018a Microplastic risk assessment in surface waters: a case study in the Changjiang Estuary, China. *Marine Pollution Bulletin* **133**, 647–654. doi: 10.1016/j.marpolbul.2018.06.020.

Xu, B., Liu, F., Brookes, P. C. & Xu, J. 2018b Microplastics play a minor role in tetracycline sorption in the presence of dissolved organic matter. *Environmental Pollution* **240**, 87–94. doi: 10.1016/j.envpol.2018.04.113.

Xu, B., Liu, F., Brookes, P. C. & Xu, J. 2018c The sorption kinetics and isotherms of sulfamethoxazole with polyethylene microplastics. *Marine Pollution Bulletin* **131**, 191–196. doi: 10.1016/j.marpolbul.2018.04.027.

Yu, F., Yang, C., Zhu, Z., Bai, X. & Ma, J. 2019 Adsorption behaviour of organic pollutants and metals on micro/nanoplastics in the aquatic environment. *Science of the Total Environment* **694**, 133643. doi: 10.1016/j.scitotenv.2019.133643.

Zhang, H., Wang, J., Zhou, B., Zhou, Y., Dai, Z., Zhou, Q., Chriestie, P. & Luo, Y. 2018 Enhanced adsorption of oxytetracycline to weathered microplastic polystyrene: kinetics, isotherms, and influencing factors. *Environmental Pollution* **243**, 1550–1557. doi: 10.1016/j.envpol.2018.09.122.

Ziajahromi, S., Neale, P. A., Rintoul, L. & Leusch, F. D. L. 2017 Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. *Water Research* **112**, 93–99. doi: 10.1016/j.watres.2017.01.042.

Ziccardi, L. M., Edgington, A., Hentz, K., Kulacki, K. J. & Driscoll, S. K. 2016 Microplastics as vectors for bioaccumulation of hydrophobic organic chemicals in the marine environment: a state of the science review. *Environmental Toxicology Chemistry* **35**, 1667–1676. doi: 10.1002/etc.3461.

Zuo, L., Li, H., Lin, L., Sun, Y., Diao, Z., Liu, S., Zhang, Z. & Xu, X. 2019 Sorption and desorption of phenanthrene on biodegradable poly (butylene adipate co-terephtalate) microplastics. *Chemosphere* **215**, 25–32. doi: 10.1016/j.chemosphere.2018.09.173.

First received 19 November 2021; accepted in revised form 24 April 2022. Available online 3 May 2022