Microplastics in drinking-water

World Health Organization

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Contents

Boxes

Executive summary

Background

Over the past few years, several studies have reported the presence of microplastics in treated tap and bottled water, raising questions and concerns about the impact that microplastics in drinking-water might have on human health. This report, which contains a summary of the evidence, key findings, recommendations and research needs, is the World Health Organization's (WHO) first effort to examine the potential human health risks associated with exposure to microplastics in the environment. The focus of this report is on the potential human health impacts of exposure to microplastics through drinking-water. However, brief information on other routes of human exposure is included for context.

This report was informed by literature reviews undertaken on the occurrence of microplastics in the water cycle, the potential health impacts from microplastic exposure and the removal of microplastics during wastewater and drinking-water treatment. Throughout the report, WHO experts examined the quality and relevance of the studies they found. The report was also informed by reviews conducted by several major entities; these are referenced throughout the report.

As a category, microplastics encompass a wide range of materials with different chemical compositions, shapes, colours, sizes and densities. There is no scientifically-agreed definition of microplastics, although most definitions focus on composition and size.

Occurrence of microplastics in water

Microplastics are ubiquitous in the environment and have been detected in marine water, wastewater, fresh water, food, air and drinking-water, both bottled and tap water.

Microplastics enter freshwater environments in a number of ways: primarily from surface run-off and wastewater effluent (both treated and untreated), but also from combined sewer overflows, industrial effluent, degraded plastic waste and atmospheric deposition. However, there are limited data to quantify the contribution of each the different inputs and their upstream sources. Further, the limited evidence indicates that some microplastics found in drinking-water may come from treatment and distribution systems for tap water and/or bottling of bottled water.

A recent systematic review of the literature identified 50 studies detecting microplastics in fresh water, drinking-water or wastewater (Koelmans et al., 2019). The lack of

standard methods for sampling and analysing microplastics in the environment means that comparisons across studies are difficult. In addition, few studies were considered fully reliable. Nevertheless, some initial conclusions can be drawn.

In fresh water, the frequency of microplastic particles by polymer type was consistent with plastic production volumes and plastic densities. A wide range of shapes and sizes were found. Only nine studies analysed microplastics in drinking-water, and fragments and fibres were the predominant shapes reported. The polymers most frequently detected were polyethylene terephthalate and polypropylene.

For both freshwater and drinking-water studies, the smallest particles detected were often determined by the size of the mesh used in sampling, which varied significantly across studies. Particle counts ranged from around 0 to 10^3 particles/L in fresh water. In drinking-water, where smaller mesh sizes are typically applied, concentrations in individual samples ranged from 0 to 10^4 particles/L and mean values ranged from 10^{-3} to 10^3 particles/L. The smallest particle size detected was 1 µm, but this result is constrained by current methods. In most cases, freshwater studies targeted larger particles, using mesh sizes that were an order of magnitude larger than those used in drinking-water studies. Thus, direct comparisons between data from freshwater and drinking-water studies cannot be made.

Possible human health risks associated with microplastics in drinking-water

The human health risk from microplastics in drinking-water is a function of both hazard and exposure. Potential hazards associated with microplastics come in three forms: the particles themselves which present a physical hazard, chemicals (unbound monomers, additives, and sorbed chemicals from the environment), and microorganisms that may attach and colonize on microplastics, known as biofilms. Based on the limited evidence available, chemicals and microbial pathogens associated with microplastics in drinking-water pose a low concern for human health. Although there is insufficient information to draw firm conclusions on the toxicity of nanoparticles, no reliable information suggests it is a concern.

Particles

Particle toxicity is dependent on a range of physical properties, including size, surface area, shape and surface characteristics, as well as the chemical composition of the microplastic particle. The fate, transport and health impacts of microplastics following ingestion is not well studied and no epidemiological or human studies on ingested microplastics have been identified. However, microplastics greater than 150 µm are not likely to be absorbed in the human body and uptake of smaller particles is expected

to be limited. Absorption and distribution of very small microplastic particles including nanoplastics may be higher, however the database is extremely limited and findings demonstrating uptake in animal studies occurred under extremely high exposures that would not occur in drinking-water. The limited number of toxicology studies in rats and mice on ingested microplastics are of questionable reliability and relevance, with some impacts observed only at very high concentrations that would overwhelm biological clearance mechanisms and that therefore do not accurately reflect potential toxicities that could occur at lower levels of exposure. Based on this limited body of evidence, firm conclusions on the risk associated with ingestion of microplastic particles through drinking-water cannot yet be determined; however at this point, no data suggests overt health concerns associated with exposure to microplastic particles through drinking-water.

Chemicals

Polymerization reactions during plastic production do not generally proceed to full completion, resulting in a small proportion of monomers such as 1,3-butadiene, ethylene oxide and vinyl chloride, that can leach into the environment. Residual monomers may also arise as a result of biodegradation and weathering of plastics. However, the extent to which this occurs is uncertain. It is likely that unbound monomers resulting from these scenarios would leach into the environment, resulting in extremely small concentrations in drinking-water sources.

Additives such as phthalate plasticizers and polybrominated diphenyl ether flame retardants are, for the most part, not covalently bound to the polymer and can more easily migrate into the environment. Migration can also be impacted by the molecular weight of additives, with small, low molecular weight molecules generally migrating at a faster rate than larger additives. Aging and weathering are likely to strongly influence migration, the overall impact of which is not well understood. However, relative to other emission routes of additives to the environment, it is anticipated that leaching from microplastic will be relatively small. If microplastics are ingested through drinking-water, the relative potential for the additives to leach from microplastics in the gastrointestinal tract is also poorly understood, with conflicting information reported in the limited number of available studies. It should be noted, however, that following the introduction of regulations limiting the use of many additives-of-concern from plastics, exposure is expected to become lower over time, although these substances can be present in older plastics which may degrade into microplastics in the environment.

The hydrophobic nature of microplastic implies that they have the potential to accumulate hydrophobic persistent organic pollutants (POPs), such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons and organochlorine pesticides. POPs indiscriminately sorb to organic carbon in the environment and therefore, the fraction of POPs sorbed

to microplastics will be small relative to other environmental media such as sediment, algae and the lipid fraction of aquatic organisms. If microplastics are ingested through drinking-water, the relative potential for POPs to leach from microplastics is not well understood and will depend on a variety of factors, including the relative size of the particle, mass of chemical accumulated, relative level of contamination within the gut, and the gastrointestinal residence time of the particle.

To assess potential health risks associated with exposure to chemicals associated with microplastics, WHO developed a conservative exposure scenario, assuming high exposure to microplastics combined with high exposure to chemicals and applied a margin of exposure (MOE) approach. Chemicals included in the assessment have been detected in microplastics, are of toxicological concern and have adequate or accepted toxicological point of departures to derive a MOE. MOEs were derived for each chemical by comparing the estimated chemical exposure for a very conservative exposure scenario to a level of exposure at which no or limited adverse effects were seen. A judgement of safety could then be based on the magnitude of this MOE. MOEs derived from the risk assessment were found to be adequately protective, indicating a low health concern for human exposure to chemicals through ingestion of drinking-water, even in extreme exposure circumstances.

Biofilms

Biofilms in drinking-water are formed when microorganisms grow on drinking-water pipes and other surfaces. Although most microorganisms in biofilms are believed to be non-pathogenic, some biofilms can include free-living microorganisms and pathogens such as *Pseudomonas aeruginosa*, *Legionella* spp., and *Naegleria fowleri*. Biofilm-forming microorganisms attach faster to hydrophobic nonpolar surfaces, such as plastics, than to hydrophilic surfaces. Environmental conditions can also influence biofilm formation on plastics and microplastics. A limited number of occurrence studies in fresh water indicate the possibility that microplastics could enable the long-distance transport of pathogens and increase the transfer of antimicrobial resistant genes between microorganisms. However, there is no evidence to suggest a human health risk from microplastic-associated biofilms in drinking-water. The risk is considered far lower than the well-established risk posed by the high concentrations and diversity of pathogens in human and livestock waste in drinking-water sources. Further, the relative concentration of microplastics in fresh water is significantly lower than other particles that pathogens can adhere to in fresh water. For microplastics that are not removed during drinking-water treatment, the relative significance of microplastic-associated biofilms is still likely negligible due to the much larger surface area of drinking-water distribution systems and their subsequent ability to support more biofilms, compared to microplastics.

Treatment technologies for removing microplastics from water

Wastewater and drinking-water treatment systems—where they exist—are considered highly effective in removing particles with characteristics similar to those of microplastics. Properties relevant to removal in water treatment include size, density and surface charge. According to available data, wastewater treatment can effectively remove more than 90% of microplastics from wastewater, with the highest removals from tertiary treatment such as filtration. Although there are only limited data available on the efficacy of microplastic removal during drinking-water treatment, such treatment has proven effective in removing far more particles of smaller size and at far higher concentrations than those of microplastics. Conventional treatment, when optimized to produce treated water of low turbidity, can remove particles smaller than a micrometre through processes of coagulation, flocculation, sedimentation/flotation and filtration. Advanced treatment can remove smaller particles. For example, nanofiltration can remove particles >0.001 µm while ultrafiltration can remove particles >0.01µm. These facts combined with well-understood removal mechanisms point to the rational conclusion that water treatment processes can effectively remove microplastics.

An important consideration is that wastewater and drinking-water treatment is not available nor optimized in many countries. Approximately 67% of the population in low- and middle-income countries lack access to sewage connections and about 20% of household wastewater collected in sewers does not undergo at least secondary treatment (UNICEF/WHO, 2019). In these places, microplastics may exist in greater concentrations in freshwater sources of drinking-water; however, the health risks associated with exposure to pathogens present in untreated or inadequately treated water will be far greater. By addressing the bigger problem of exposure to untreated water, communities can simultaneously address the smaller concern related to microplastics in surface water and other drinking-water supplies.

Another factor to consider is how treatment waste is handled. Plastics are not usually destroyed, but rather transferred from one phase to another. For this reason, water treatment waste needs to be considered as a potential source of microplastics contamination in the environment. There are currently limited data available on how treatment wastes are handled and the impact they may have on the environment.

Managing plastic and microplastic pollution in the environment

Irrespective of whether there are any risks to human health from ingestion of microplastics in drinking-water, there is a need to improve management of plastics

and reduce plastic pollution to protect the environment and human well-being. Poorly managed plastic can contribute to sanitation-related risks and air pollution, and impact tourism and overall quality of life. If plastic emissions into the environment continue at current rates, there may be widespread risks associated with microplastics to aquatic ecosystems within a century (SAPEA, 2019), with potentially concurrent increases in human exposure.

In response to concerns about the impact of plastic and microplastic pollution, public engagement and political commitment has increased. More than 60 countries are already taxing or banning single-use plastics, primarily plastic bags (UNEP, 2018).

Strategies to reduce the number of plastics released into the environment are critical to the effort to minimize adverse impacts of discarded plastics. Where simple, low cost actions can be taken to make even a small difference to plastic inputs to the environment, it would be sensible to implement them. Actions could include improving recycling programmes, reducing littering, improving circular solutions, reducing the use of plastics where possible and decreasing waste inputs into the environment by industry. Care must be taken, however, when considering mitigation strategies so that addressing one problem does not simply result in the creation of a new one. This is particularly important in view of the limited data on sources of different sizes and types of microplastics, including the very small particles that are currently not well quantified. The benefits of plastic must also be considered before introducing policies and initiatives. For example, single-use syringes play an important role in preventing infections. Priority management actions should be "no regrets," in that they confer multiple benefits and/or that they are cost-effective.

Recommendations

Routine monitoring of microplastics in drinking-water is not recommended at this time, as there is no evidence to indicate a human health concern. Concerns over microplastics in drinking-water should not divert resources of water suppliers and regulators from removing microbial pathogens, which remains the most significant risk to human health from drinking-water along with other chemical priorities. As part of water safety planning, water suppliers should ensure that control measures are effective and should optimize water treatment processes for particle removal and microbial safety, which will incidentally improve the removal of microplastic particles.

However, for researchers, it would be appropriate to undertake targeted, well-designed and quality-controlled investigative studies to better understand the sources and occurrence of microplastics in fresh water and drinking-water, the efficacy of different treatment processes and combinations of processes, and the significance

of the potential return of microplastics to the environment from treatment waste streams including the application of sludge biosolids to agricultural land.

Measures should also be taken to better manage plastics and reduce the use of plastics where possible, to minimize plastic and microplastic pollution despite the low human health risk posed by exposure to microplastics in drinking-water, as such actions can confer other benefits to the environment and human well-being.

Research needs

To better assess human health risks and inform management actions, a number of research gaps need to be filled. With respect to exposure, there is a need to better understand microplastics occurrence throughout the water supply chain, using quality-assured methods to determine the numbers, shapes, sizes, composition and sources of microplastics and to better characterize the effectiveness of water treatment. Research is also needed to better understand the significance of treatment-related waste streams as contributors of microplastics to the environment.

With respect to potential health effects, quality-assured toxicological data are needed on the most common forms of plastic particles relevant for human health risk assessment. Further, a better understanding on the uptake and fate of microplastics and nanoplastics following ingestion is needed.

Finally, given that humans can be exposed to microplastics through a variety of environmental media, including food and air, a better understanding of overall exposure to microplastics from the broader environment is needed.

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Literature reviews were undertaken for the sections on health effects and treatment. The information on occurrence was based on a systematic review (Koelmans et al., 2019) that WHO commissioned on occurrence of microplastics in drinking-water, fresh water and wastewater and quality of these studies. The report has also been informed by reviews from several major bodies and these are referenced throughout the report.

Lead authors:

- Pete Marsden, Drinking Water Inspectorate, UK
- Bart Koelmans, Wageningen University, Netherlands
- Julie Bourdon-Lacombe, Health Canada, Canada
- Todd Gouin, Independent Consultant, UK
- Lesley D'Anglada, US Environmental Protection Agency, USA
- David Cunliffe, South Australia Health, Australia
- Peter Jarvis, Cranfield University, UK
- John Fawell, Cranfield University, UK
- Jennifer De France, WHO, Switzerland

Experts who provided insights, wrote text, offered peer review, and/or participated in meetings:

- Nick Ashbolt, University of Alberta, Canada
- Virunya Bhat, WHO Collaborating Centre, NSF International, USA
- Richard Brown, WHO, Switzerland
- Claus Gerhard Bannick, German Environment Agency, Germany
- Ruth Bevan, Independent Consultant, UK
- Allen Burton, University of Michigan, USA
- Enrique Calderon, Buenos Aires University, Argentina
- Richard Carrier, Health Canada, Canada
- Joseph Cotruvo, Joseph Cotruvo & Associates, USA
- Ana Maria de Roda Husman, National Institute of Public Health and the Environment, Netherlands

- Alexander Eckhardt, German Environment Agency, Germany
- Gunnard Gerdts, Alfred Wegener Institute, Germany
- Bruce Gordon, WHO Switzerland
- Francis Hassard, Cranfield University, UK
- Andrew Humpage, Independent Consultant, Australia
- Paul Hunter, University of East Anglia, UK
- Pranav Joshi, Singapore Food Agency, Singapore
- Christine Lemieux, Health Canada, Canada
- Stéphanie McFadyen, Health Canada, Canada
- Rory McKeown, WHO, Switzerland
- Kate Medlicott, WHO Switzerland
- Gertjan Medema, KWR Water Research Institute and Delft University of Technology, Netherlands
- Choon Nam Ong, National University of Singapore, Singapore
- Angella Rinehold, WHO, Switzerland
- William Robertson, Watermicrobe Consultancy, Canada
- Chelsea Rochman, University of Toronto, Canada
- Lisa Scheuermann, WHO, Switzerland
- Mark Sobsey, University of North Carolina at Chapel Hill, USA
- Shuhei Tanaka, Kyoto University, Japan
- Emanuela Testai, Istituto Superiore di Sanità, Italy
- Richard Thompson, University of Plymouth, UK
- Angelika Tritscher, formerly WHO, Switzerland
- Rhodes Trussell, Trussell Technologies, USA
- Wolfgang Uhl, Norwegian Institute for Water Research and Department of Civil and Environmental Engineering, Norway
- Annemarie van Wezel, University of Amsterdam, Netherlands
- Stephanie Wright, King's College, UK
- US Environmental Protection Agency, USA (Christine Bergeron, William Boyes, Robert Burgess, Jimmy Chen, Mary Davis, Rick Greene, Kay Ho, Greg Miller, Edward Ohanian, Stig Regli, Ken Rotert, Jamie Strong, Lili Wang, Rich Weisman, Richard Zepp)

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Acronyms and abbreviations

BMDL	lower confidence limit on the benchmark dose
BPA	bisphenol A
BW	body weight
DEHP	di(2-ethylhexyl)phthalate
DDT	dichlorodiphenyltrichloroethane
DWTP	drinking-water treatment plant
ECHA	European Chemicals Agency
EFSA	European Food Safety Authority
FTIR	fourier transform infra-red spectroscopy
FAO	Food and Agriculture Organization of the United Nations
GC	gas chromatography
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GI	gastrointestinal
ISO	International Organization for Standardization
LOAEL	lowest-observed-adverse-effect level
LoD	limit of detection
LoQ	limit of quantification
MOE	margin of exposure
MS	mass spectrometry
Mt	million tonnes
NOAEL	no-observed-adverse-effect level
PA	polyamides
PAHs	polycyclic aromatic hydrocarbons
PBDEs	polybrominated diphenyl ethers
PC	polycarbonates
PCBs	polychlorinated biphenyls
PE	polyethylene
PET	polyethylene terephthalate
PFAS	per- and polyfluoroalkyl substances
POD	point of departure
POPs	persistent organic pollutants
PP	polypropylene
PS	polystyrene
PUR	polyurethane
PVC	polyvinyl chloride
SAPEA	Science Advice for Policy by European Academies
TAS	total accumulated score
UNEP	United Nations Environment Programme
UV	ultraviolet
WHO	World Health Organization
WWTP	wastewater treatment plant

1. Introduction

1.1 Purpose of this report

This report focuses on the occurrence of microplastics in drinking-water and the potential risks to human health that may be associated with such exposure. The target audience includes drinking-water regulators, policy makers and water suppliers. The purpose of this report is to increase understanding on the issue of microplastics in drinking-water and to summarize how current knowledge might influence policy and management actions as well as research needs. Given the broad interest in plastic and microplastic pollution, this document may also be of interest to researchers, the public and civil society groups concerned with plastic pollution. Additionally, a separate information sheet has been prepared that summarizes the key findings and conclusions in this report that the public and other stakeholders may find useful. This report, focused specifically on bottled water and tap water, marks the beginning of WHO's effort to assess the potential human health risks associated with exposure to microplastics in the environment.

1.2 Scope of this report

This document summarizes the latest knowledge on microplastics in drinking-water. It references other routes of human exposure such as food and air to provide a benchmark for the relative significance of exposure via drinking-water. It does not cover the extensive literature relating to the potential ecological effects of microplastics in the wider environment (see Box 1.1). Nanoplastics are considered in this report, although at present there is insufficient information available for an in-depth evaluation.

Box 1.1 The risk of microplastics to aquatic ecosystems

There is a growing body of literature on the possible ecological effects of microplastics in freshwater environments and extensive literature on plastics of all sizes in the marine environment. Oceans serve as the ultimate sink for much of the world's mismanaged plastic and microplastic waste, including from freshwater environments. While the literature has been reviewed elsewhere (GESAMP, 2015, 2016; FAO, 2017; SAPEA, 2019) and is not repeated here, the key conclusions are that although large pieces of plastic are harmful to marine life, the impact of microplastics is less certain. However, there may be widespread risks to aquatic ecosystems within a century if microplastic emission in the environment continues at the current rate (SAPEA, 2019). It is important to make clear though, that risks to the aquatic ecosystem do not necessarily equate to human health risks.

Brief background information is provided on plastic production and the value of plastics to society (section 1.3), since policy and management actions (Chapter 6) should also consider the broader benefits of plastics.

The state of knowledge on microplastics is evolving rapidly, as evidenced by the significant increase in the number of recent publications, including research articles that address the issue. A number of initiatives are being taken up by governments, universities and other stakeholders to better understand the occurrence of microplastics in freshwater environments and drinking-water as well as the effectiveness of water treatment technologies. This report may therefore be updated once a significant body of further evidence becomes available. Currently, WHO is focusing efforts on a more in-depth assessment of potential human health risks of microplastics in the environment and intends to publish a complementary report to this document.

1.3 Background

Interest in microplastics in drinking-water was stimulated initially by studies (Kosuth, Mason and Wattenberg, 2018; Mason, Welch and Neratko, 2018) that reported the presence of microplastics in tap water and in bottled water. Since then, several additional studies have been published (Oßmann et al., 2018; Pivokonsky et al., 2018; Schymanski et al., 2018; Strand et al., 2018; Uhl, Eftekhardadkhah and Svendsen, 2018; Mintenig et al., 2019) leading to genuine questions and concerns about whether the presence of microplastics in drinking-water poses a risk to human health. Risk, however, is a function of both hazard and exposure, and the presence of microplastics in drinking-water does not necessarily equate to a risk to human health. With scant data available on both hazard and exposure, WHO collated and reviewed existing information on the occurrence of microplastics in drinking-water, consequent human exposure via drinking-water, and the potential effects on human health. Since fresh water provides a vital source of drinking-water, occurrence of microplastics in fresh water was also reviewed, as were data on removal in drinking-water treatment which offers an effective barrier to a wide range of particles.

1.3.1 Definitions of microplastics

The definition of **microplastics** is not completely straightforward. Microplastics represent a diverse range of material types, shapes, colours and sizes (Thompson, 2015). To account for these complexities, researchers have proposed definitions for plastic debris (Hartmann et al., 2019) and microplastics (Verschoor, 2015), for example, by describing them according to specific criteria. Because of the different methods used to collect and quantify microplastics, it was not possible to apply a uniform definition

to the results of existing studies. However, the lack of a uniform definition does not impact this assessment, nor the conclusions in this report.

Most definitions in the literature focus on composition and size. A widely used definition describes microplastics as plastic particles smaller than 5 mm in length. However, this is a rather arbitrary definition and is of limited value in the context of drinking-water since particles at the upper end of the size range are unlikely to be found in treated drinking-water. Some groups define a lower bound at about 1 µm. The lower bound is often simply a function of the sampling and analytical technique used in the study. A subset of microplastics smaller than 1 µm in length are often referred to as **nanoplastics**, but again with an inconsistent upper bound.

As for the composition of microplastics, there is again no standard definition. Many studies focus on particles made from synthetic polymers rather than using the International Organization for Standardization (ISO) definition, which excludes elastomeric materials (ISO, 2013). The German Federal Ministry of Education and Research defines plastics as a subgroup of polymers including elastomers and modified natural polymers (Braun et al., 2018). The European Chemicals Agency (ECHA, 2019) uses solid polymer-containing particles but excludes natural polymers that have not been modified.

Microplastics are sometimes categorized as two types, primary and secondary. **Primary microplastics** are specifically manufactured in the microplastic size range, for example industrial abrasives used in sandblasting and microbeads used in cosmetics. **Secondary microplastics** are formed by the fragmentation and weathering of larger plastic items (e.g. bags, bottles, clothing, tyres, etc.) either from wear or from their release into the environment.

1.3.2 Plastic production and types

Plastics are formed by the reaction of small organic molecules called monomers resulting in long polymer chains. Some polymers, such as polyethylene (PE), are formed by addition polymerization. Others, such as nylon, are formed by condensation reactions in which small molecules, often water, are eliminated in the process of creating a longer chain.

The polymers used to make a plastic are almost always mixed with additives, including colourants, plasticizers, stabilizers, fillers, and reinforcements. These additives affect the chemical composition, chemical and mechanical properties and cost of the plastic.

There are two general types of plastics: thermoplastics and thermoset plastics. **Thermoplastics** soften when heated, can be reformed and then harden when cooled. This process can be repeated numerous times, which means thermoplastics can be recycled. Thermoplastics include PE (used in toys, shampoo bottles, pipes,

etc.), polypropylene (PP—used in food packaging, snack wrappers, auto parts, etc.), polyethylene terephthalate (PET—often used for water and other beverage bottles), polystyrene (PS—used in foam food containers, eyeglasses, building insulation, etc.), polyvinylchloride (PVC—used in window frames, pipes, cable insulation, etc.), and others including polycarbonates (PC) and polyamides (PA). **Thermoset plastics** will not soften upon heating because permanent chemical bonds form between polymer chains (crosslinking). Thermoset plastics include polyurethane (PUR—used in building insulation, pillows and mattresses, insulating foams, etc.), epoxy resins, some acrylic resins and some polyesters.

In the context of drinking-water, PE and PVC are used in water distribution mains and epoxy resins, PUR for relining existing mains, PP for various components and PA as coagulant aids in water treatment. Plastics are also used in membrane filters in water treatment systems. In the context of bottled water, PET is often used to make the bottles and PP and PE to make bottle caps. These materials are often regulated to ensure they do not leach substances (e.g. monomers, plasticizers or other additives) at concentrations of concern into drinking-water.

Biodegradable plastics are plastics that can be decomposed by hydrolysis or ultraviolet (UV) light degradation or the action of microorganisms, usually bacteria. They can be made from either renewable raw materials or from petrochemicals. However, some "biodegradable" plastics require prolonged exposure to temperatures above 50°C to degrade completely. Such conditions exist in industrial composting but are rarely, if ever, met in the environment. Some plastics contain pro-oxidants which promote fragmentation, but there is some controversy as to whether there is any actual biodegradation of these plastics in the environment because they have the potential to form microplastics (UNEP, 2015).

1.3.3 Estimates of global quantities of plastics produced

World plastic production has increased roughly exponentially since large-scale production first began in the 1950s (see Figure 1.1). Global plastic production, excluding fibres, increased from 322 million tonnes (Mt) in 2015 (Plastics Europe, 2017) to 348 Mt in 2017 (Plastics Europe, 2018). With fibres included, global production was estimated to be 381 Mt in 2015 and with additives included, 407 Mt (Geyer, Jambeck and Law, 2017). Considering the estimated worldwide population growth rate and current consumption and waste habits, plastic production is predicted to double by 2025 and more than triple by 2050 (FAO, 2017).

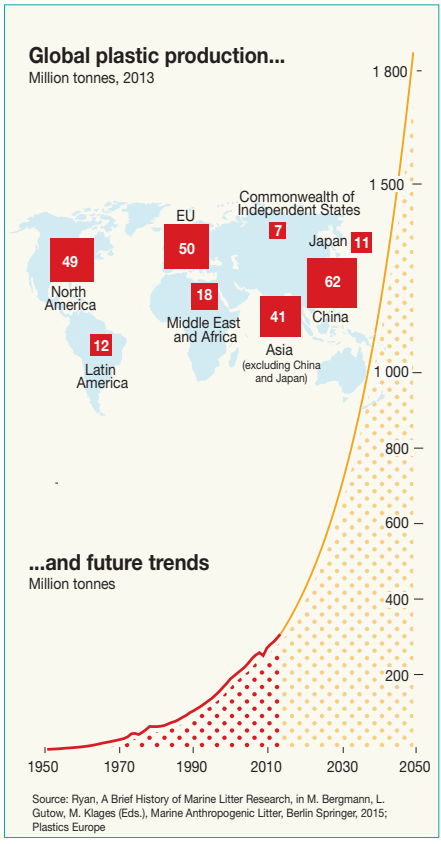
Of total non-fibre plastic production, 36% is PE, 21% is PP, 12% is PVC, and less than 10% each are PET, PUR and PS. The production of polyester PAs and acrylics fibre is

the next largest group, much of which is PET. Together, these seven groups account for 92% of all plastics ever made (Geyer, Jambeck and Law, 2017). Intentional microplastic production represents <0.1% of total plastic production based on European figures from ECHA (2019) and Plastics Europe (2018).

1.3.4 Value to society

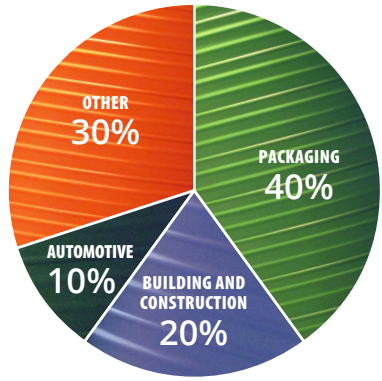
The proliferation of plastics can be attributed to their many desirable attributes. Different plastics have different properties; they can be inexpensive, flexible, robust, lightweight, waterproof, easy to clean and sterilize, and act as insulators. They are often the most economical and sometimes only option in certain applications. Plastics are common in packaging, building and construction materials, the automotive industry, electrical and electronic parts, household leisure and sports products and the agricultural sector. Plastics are also used in a wide variety of other products; see Figure 1.2 for a breakdown of production estimates in Europe by industry (Plastics Europe, 2018). In some cases, plastics confer human health-related advantages, for example, plastics can increase the shelf-life of food by preventing microbial contamination. In the medical field, plastics are used in a variety of critical applications including in examination gloves, syringes and intravenous tubes, and they provide an inert material for less common but important uses including heart valves and prosthetics.

Fig. 1.1 Global plastic production



Credit: Maphoto/Riccardo Pravettoni (http://www.grida.no/resources/6923).

Fig. 1.2 Total non-fibre plastic production in Europe



Economically, the plastic industry provides employment to millions of people. The European plastic industry, for instance, is estimated to involve 60 000 companies employing 1.5 million people, with a turnover of 355 billion Euros. The European industry represents 18.5% of the annual global plastics market of 348 Mt in 2017 (Plastics Europe, 2018). Globally, employment and turnover may be five times the European estimate.

1.4 Overview of contents

Below is a brief description of each chapter to assist the reader in navigating the contents of this report.

Chapter 2: Occurrence of microplastics in fresh water and drinking-water
This chapter summarizes what is known about the occurrence of microplastics in fresh water and drinking-water and describes the possible sources and transport of microplastics into the freshwater environment. It also includes information on sampling and analytical methods, the quality of the occurrence studies and, for comparative purposes, some information on microplastics in food and air.

Chapter 3: Possible human health risks associated with microplastics in drinking-water: particles and chemicals
The potential hazards associated with microplastics in drinking-water include particles, chemicals and biofilms. This chapter examines microplastic particles and chemicals, including those that make up plastics: monomers and additives, as well as chemicals from the environment that may sorb to microplastics. The relevant health effects data for microplastic particles are summarized and information is presented on potential human health risks in the context of exposure.

Chapter 4: Possible human health risks associated with microplastics in drinking-water: biofilms
This chapter examines the growth of microorganisms, or biofilms, on microplastics and the associated possible risks to human health.

Chapter 5: Treatment technologies for removing microplastics from water
Drinking-water treatment has an important role in reducing concentrations of microplastics that have been introduced into source waters. This chapter therefore discusses the effectiveness of drinking-water treatment in removing microplastics. Since wastewater effluent has been identified as a key source of microplastics in surface waters, an overview of the effectiveness of wastewater treatment is also provided.

Chapter 6: Managing plastic and microplastic pollution in the environment
This chapter discusses the benefits of plastic and microplastic waste management and options to minimize plastic pollution into the environment.

Chapter 7: Conclusions, recommendations and knowledge gaps
This chapter summarizes key conclusions and research needs and recommends actions for drinking-water regulators, policy-makers and water suppliers.

Annex1 supplements the information included in Chapter 2. It includes a summary of a recent WHO-commissioned review of the literature by Koelmans et al. (2019) on occurrence of microplastics in drinking-water, fresh water and wastewater. It also includes a more in-depth summary of the available drinking-water studies.

2. Occurrence of microplastics in fresh water and drinking-water

2.1 Introduction

This section summarizes what is known about the occurrence of microplastics in fresh water and drinking-water. The chapter begins with background information on the possible sources and transport of microplastics into the freshwater environment; the variety of methods used for sampling and analysis; the quality of existing occurrence studies; and recommendations on how to improve study methods. It then presents data from occurrence studies along with data on polymer types and particle shapes. For comparative purposes, some data on the presence of microplastics in food and air are included.

2.2 Sources and transport of microplastics into water

Tracing the sources and transport of microplastics in the environment is a complex task. Little is understood about the processes that govern the transport of microplastics through freshwater environments. However, key factors influencing their transport and distribution will be the inherent properties of the microplastics, i.e. their density, size and shape. Common consumer plastics range in density from 0.85 to 1.41 g/cm^3 (Eerkes-Medrano, Thompson and Aldridge, 2015). This range straddles the density of fresh water (1 g/cm^3) so some microplastics will sink and some will float in water. The density of the microplastic, and hence where it sits in the water column, will also be influenced by the formation of a biofilm on its surface (Shah et al., 2008; see Chapter 4 for information on biofilms). The densities of a range of plastics are included in Table 2.1.

Given the diverse uses of plastics, the many different shapes and types of microplastics and the myriad routes to freshwater environments, it is extremely difficult to pinpoint or quantify all sources of microplastics to freshwater environments. Available information on inputs of microplastics into the aquatic environment is often based on modelling, and there are insufficient data to accurately validate these modelled estimates. Further, there are insufficient methods to track the sources and transport of microplastics in the environment (SAPEA, 2019). Nevertheless, there is a general tendency to observe higher concentrations of microplastics in areas near densely populated urban centres (Eriksen et al., 2013; Baldwin, Corsi and Mason, 2016). A recent review of the literature (Alimi et al., 2018) estimates loads into different

environmental compartments. Sources of microplastics into fresh water included: run-off from land-based sources, wastewater effluents and mishandled plastic wastes. Each of these and other potential sources are described below.

Table 2.1 Polymer densities

Polymer	Density g/cm^3 (low range)	Density g/cm^3 (high range)
Polypropylene	0.9	0.91
Polyethylene	0.965	0.971
Styrene butadiene rubber[a]	0.98	0.98
Polyamide (nylon)	1.02	1.05
Polystyrene	1.04	1.1
Acrylic	1.09	1.2
Polyvinyl chloride	1.16	1.58
Polymethacrylate	1.17	1.2
Polyurethane	1.2	1.2
Polyester	1.23	2.3
Polyethylene terephthalate	1.37	1.45

[a] Harandi et al., (2017)

Source: Reprinted (adapted) with permission from *Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification*, Hidalgo-Ruz et al., Environ. Sci. Technol., 2012, 46 (6), pp 3060–3075. Copyright (2012) American Chemical Society.

2.2.1 Run-off from land-based sources

Several studies (Sundt, Schulze and Syversen, 2014; Lassen et al., 2015; Sherrington et al., 2016; Boucher and Friot, 2017) have attempted to characterize the various inputs of microplastics into the aquatic environment from land-based sources, although many of these studies have focused on inputs into the marine environment. Land-based sources of microplastics into the aquatic environment, including fresh water, can originate from a variety of activities, infrastructure and land use practices. For instance, road surface run-off from the breakdown of road-marking paints and tyre wear debris has been suggested to be a significant input (Verschoor, 2016; FWR, 2017). Another important land-based source of microplastics is microplastic fibres that are released from textiles due to wear-and-tear and washing (Lassen et al., 2015; Henry, Laitala and Klepp, 2019; Schöpel and Stamminger, 2019). "City dust", which is used to describe a number of sources related to abrasion of objects, such as synthetic soles of footwear and artificial turfs, can collectively be significant (Boucher and Friot, 2017). Finally, agricultural run-off has been identified as a potential source of microplastics in freshwater environments, particularly where sewage sludge has been applied to the land or where agricultural plastics, such as those used for mulching, have been used (Horton et al., 2017).

2.2.2 Wastewater effluent

Wastewater effluent is another widely recognized source of microplastic pollution in fresh water (FWR, 2017; WE&RF, 2017). Increases in microplastic concentrations downstream of effluent discharge compared to upstream have been reported in the UK (Kay et al., 2018) and the USA (McCormick et al., 2014). As summarized by the Science Advice for Policy by European Academies (SAPEA, 2019), synthetic textile fibres from clothes washing, cosmetic microbeads[1] and disintegrated parts of larger consumer products that are flushed down toilets and sinks are major domestic inputs into sewage systems (see Box 2.1).

Box 2.1 Lack of sewage treatment: the bigger problem?

Although treated wastewater effluent is recognized as an input of microplastics in fresh water, well-equipped sewage treatment can effectively remove most microplastics from the effluent (see section 5.2). Most wastewater in high-income countries is in fact collected in sewers and then treated. However, in low- and middle-income countries, only 33% of the population have sewer connections. Wastewater for the remaining 67% of the population is collected and treated in onsite systems or discharged directly to soil and water bodies (UNICEF/WHO, 2019). Therefore, the lack of wastewater treatment or other appropriate systems for collecting and treating wastewater may be the more significant issue.

The large volume of effluent produced from wastewater treatment means that, even with effective removal, high absolute numbers of microplastics can be discharged. One study calculated that 65 million microplastic particles were released each day in the effluent from a wastewater treatment plant (WWTP), equating to approximately 100 particles/population-equivalent/day (Murphy et al., 2016). Such estimates are highly variable, for example, Carr, Liu and Tesoro (2016) estimated that for every microplastic particle discharged to the environment from wastewater treatment, 1140 L of water was discharged from a secondary WWTP. Based on 120 L water use/person/day, this is three orders of magnitude below the per-capita estimate quoted above.

2.2.3 Combined sewer overflows

Combined sewer overflows designed to cope with storm events and heavy rainfall can also be direct sources of microplastics in fresh waters since the barrier provided by wastewater treatment is temporarily bypassed (FWR, 2017).

[1] Inputs of cosmetic microbeads into the aquatic environment, while considered minor compared to other sources (Boucher and Friot, 2017; WE&RF, 2017), have been minimized after voluntary initiatives from the industry and government restrictions on the use of microbeads in wash-off cosmetics in a number of countries (e.g. Defra and Gove, 2018).

2.2.4 Industrial effluent

The relative contribution of industrial effluents to microplastics in wastewaters has yet to be investigated (van Wezel et al., 2018 as cited in SAPEA, 2019). However, industry-related microplastics have been reported in fresh waters. In particular, pre-production pellets have been detected in the Great Lakes, the Danube River and a river in the Los Angeles basin (Eerkes-Medrano, Thompson and Aldridge, 2015). Whilst these pellets may represent a concern to aquatic wildlife, they will not be found in treated drinking-water because of their size. However, if they are degraded to smaller microplastics, they may pose more of a challenge to drinking-water treatment processes. Some PE manufacturers have installed fine-meshed filters on the outgoing storm and process water in an effort to significantly reduce emissions (Lassen et al., 2015).

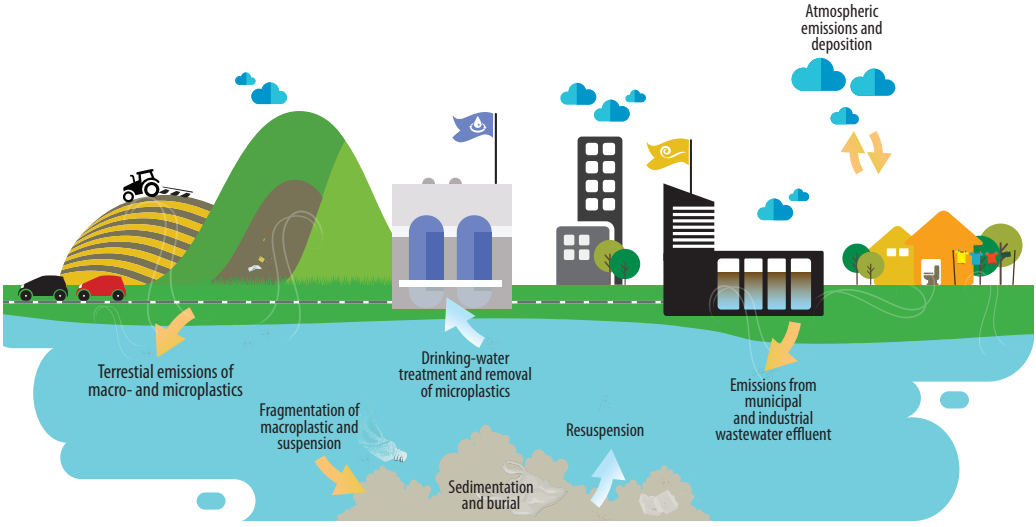
2.2.5 Fragmentation and degradation of macroplastics

Macroplastic debris originating from urban environments can enter freshwater systems (Gasperi et al., 2014; Morritt et al., 2014) and may also represent an important source of microplastic formation by fragmentation. Data are limited on the rates of fragmentation and degradation of macroplastics in the marine or freshwater environment. Nevertheless, the large volumes of macroplastics observed in the marine environment have been suggested to be a significant source of microplastics, as it is assumed that these materials will eventually fragment and degrade (Barnes et al., 2009). Once macroplastic debris has reached the aquatic environment, UV radiation and high temperatures can cause chemical changes, making plastics brittle and thus more susceptible to fragmentation and degradation (Andrady, 2007a; Andrady, 2007b). Similar processes are likely to operate in freshwater and marine environments. Zbyszwski and Corcoran (2011) examined degradation patterns of microplastics in fresh waters using a scanning electron microscope and found them similar to those found on marine beaches (Corcoran, Beisinger, and Grifi, 2009). Hüffer et al. (2017) noted that in estimating the amount of secondary microplastics formed, the total production volume may be less relevant than the release processes and subsequent fragmentation in the environment. It is possible that further fragmentation of microplastics to nanoplastics can occur and Alimi et al. (2018) has stated that "although environmental levels of nanoplastics are yet to be quantified, plastic nanolitter is expected to be as ubiquitous as its bulk counterparts."

2.2.6 Atmospheric deposition

Atmospheric deposition has been identified as an additional potential contributor to microplastics in freshwater environments through wet and dry deposition, precipitation and run-off (Wright and Kelly, 2017). Further information on airborne microplastics is included in section 2.8.2.

Fig. 2.1 Examples of routes by which plastics and microplastics enter and move in the freshwater environment and how microplastics may reach drinking-water



The schematic above (Figure 2.1) outlines some potential sources and transport mechanisms of plastics and microplastics in fresh water in relation to how microplastics may reach drinking-water.

2.2.7 Drinking-water production and distribution

While drinking-water treatment provides an effective barrier to a wide range of waterborne particles, including, probably to microplastics (see section 5.3), some treatment-plant components and distribution networks are made from plastic and their erosion or degradation may contribute to microplastics in drinking-water (Mintenig et al., 2019). Similarly, the bottles and caps of some bottled waters are made of plastic, which themselves may be a source of microplastics in drinking-water (Oßmann et al., 2018; Schymanski et al., 2018—see section A.4 for further information).

2.3 General principles of sampling and analysis

Historically, analysis for microplastics has focused on environmental samples. However, there is currently no standard method for sampling and analysis of microplastics in the environment, although ISO are currently looking at this issue and a number of reviews have been conducted to compare methods (ISO, in press; Hidalgo-Ruz et al., 2012; Li, Liu and Chen, 2018).

Sampling and analysis involves three complex steps: (1) sampling; (2) sample extraction and isolation; and (3) identification, characterization and quantification. The environmental medium being examined (e.g., water, sewage sludge or effluent) determines the procedures required for sampling and preparation. Methods for drinking-water are derived from those used in environmental water samples, but few studies have been conducted and, again, there is no agreement on a standard method.

There is currently no standard method for sampling and analysis of microplastics in the environment.

2.3.1 Sampling

Microplastic samples can be acquired using trawl nets (typically 300 µm) drawn across the surface of the water, or through collection of water samples from which the particles are extracted later. Initial sample purification usually involves filtration, followed by some sort of extraction process such as density separation, in which samples are mixed with a liquid of defined density, allowing microplastic particles to float and heavier particles to sink (see Table 2.1 for a list of plastics and their densities). Further purification may require chemical or enzymatic methods to remove organic or inorganic contaminants (biofouling). The extent of the preparation is dependent on the nature of the samples: dirtier samples will require more preparation. Since treated drinking-water and bottled water are relatively clean media, some of the purification steps required for other environmental samples may not be necessary.

2.3.2 Analysis

Microplastics are recovered from the supernatant and filtered or sieved. The concentrate may be visually sorted before quantification by microscopic counting with or without tagging using dyes, but neither of these methods can unambiguously confirm the particles are plastics.

Three different approaches are available to determine the chemical composition and/or size of plastic particles: spectroscopic, thermoanalytical, and chemical. These methods are described briefly below. For further information about these methods, including capabilities and limitations related to detection levels and the ability to detect particle dimensions, see Braun et al. (2018).

Spectroscopic methods are used to identify the specific chemical structure of polymers by comparing their absorption or emission spectra with reference spectra. Fourier transform infrared spectroscopy (FTIR) is a well-established, relatively fast and reliable spectroscopic method that, when coupled with microscopy, can identify particles to about 10–20 µm. However, biofilms, if not removed, can interfere with the detection

of microplastics. FTIR also requires expensive instrumentation not available in many laboratories. Microscopy coupled with Raman spectroscopy can identify particles in the 1–20 µm range. However, it can be subject to interference, may be slow, and also requires expensive instrumentation.

With thermoanalytical methods, the sample is pyrolysed under inert conditions, so that specific decomposition products of the individual polymers can be analyzed. These methods tend to require larger particle masses compared to spectroscopic methods. Pyrolysis-gas chromatography/mass spectrometry (GC/MS) can provide information on additives as well as the polymer, and if the sample is large enough, can identify the polymer composition of nanoplastic particles.

Conventional chemical methods such as inductively coupled plasma mass spectrometry can be used to decompose the samples and detect specific fragments of polymers or elements. Again, these tend to require larger particle masses (Braun et al., 2018).

Software packages are often used in both tagging and spectroscopic studies to recognize and count particles and to characterize particles by comparing them with library spectra.

2.4 Overall reliability of studies

Throughout the sampling and analysis process, careful controls need to be in place to avoid contamination, as microplastics are ubiquitous in the environment. A systematic review of 50 studies on microplastics in fresh water, drinking-water and wastewater commissioned by WHO (Koelmans et al., 2019) concluded that methods for microplastic sampling and analysis of water samples need to be improved for reproducibility and comparability of results. To determine the reliability of the studies, Koelmans et al. (2019) applied nine quality control criteria adapted from criteria developed for biota samples (Hermsen et al., 2018). Only 4 of 50 studies received positive scores in all criteria. A full 46 studies were not considered reliable on at least one crucial criterion. Areas requiring the most improvement included sample treatment, polymer identification, laboratory preparation, clean air conditions and positive controls. The fact that data or a study may not be fully reliable according to these criteria does not imply that the data are not useful.

The majority of microplastic occurrence studies are not considered fully reliable. There is a significant need to improve the quality assurance of occurrence studies on microplastics.

Some improvements in quality assurance for sampling and analysis methods may have already occurred since the four studies that received positive scores in all criteria were the more recent ones, published in 2017 and 2018. Average quality scores were

highest in the studies assessing bottled water, followed by tap water, water from a drinking-water treatment plant (DWTP), surface water and wastewater. This ranking likely reflects the relative ease of analysing the different water types (Koelmans et al., 2019). Further details on the systematic review including the nine key quality control criteria are summarized in the annex and recommendations to improve sampling and analytical methods are included in Box 2.2.

Box 2.2 Recommendations to improve sampling and analytical methods

There is a general need to improve microplastic sampling and analysis in water samples. The following improvements are considered to be particularly important:

1. Studies should provide complete information about the method of sampling so that it can be reproduced.
2. The sample volumes will depend of the nature of the water being sampled and size of the particles being analysed, which in turn is determined by the filter or mesh size being used. Sample volumes should be sufficiently large to reliably detect low microplastic concentrations.
3. Wherever possible, plastic material should be avoided for sampling and analyses. If plastic material must be used, it should be characterised and reported.
4. Materials should be rinsed with filtered water to avoid contamination.
5. Sampling and sample processing should be carried out by trained professionals or the quality of samples collected or processed by volunteers should be (quantitatively) validated against results obtained by professionals.
6. If preservatives are used, their ability to affect polymer mass or particle shapes should be tested, either in the context of the study or via literature support.
7. Laboratory surfaces should be thoroughly cleaned with filtered water to avoid contamination.
8. All samples should be handled in a laminar-flow hood or in a clean-air laboratory.
9. Blanks should be run, per day or per series, at least in triplicate, to verify and correct for contamination and results should be corrected against blanks.
10. Positive controls should be used to verify the recovery of particles during digestion, density separation and filtration steps.
11. Digestion should be applied when necessary. Usually digestion is not necessary for drinking-water from a treated source. However, for surface water and wastewater samples, where high organic matter concentrations hamper the selection and (visual) identification of particles, a digestion step is required.
12. Polymer identification is required for a representative subsample of the entire sample.
13. Data should be reported as number of particles/L and mass/L together with their detection limits. Minimum and maximum particle sizes and when possible, morphologies should be specified. All these characteristics may inform the risk assessment.
14. Standard methods of sampling and analysis should be developed but may differ for the different media being sampled. For example, sediment methods may differ from seawater methods which will also differ from drinking-water methods. As far as possible the same principles need to be followed.

2.5 Microplastic concentrations reported in fresh water

Microplastics are frequently present in the freshwater environment, with studies reporting particle counts ranging from around 0 to 10^3 particles/L (Koelmans et al., 2019). The relative concentration of microplastics detected is dependent on the location, the sampling technique (mesh size) and method of analysis. Larger sieves will not retain small particles, so total particle numbers will be lower from samples taken with large sieves than from small sieves.

In Koelmans et al. (2019), 31 studies of microplastics in fresh water were identified and the six highest-scoring studies in terms of methodological quality (studies with a total accumulated score (TAS), greater than nine or 50% of the maximum value), are summarized in Table 2.2 below. The reported concentrations of microplastics ranged from averages of 4.7 particles/L in the study using a 48 µm sieve down to 0.00026 particles/L in a study using a 333 µm sieve. Not surprisingly, the one groundwater study found low concentrations of microplastics relative to other water types despite using a very small sieve size (3 µm). A priori, low particle counts would be expected in many groundwaters because of the protection afforded by the overlying strata.

Table 2.2 Summary of reported microplastic particle numbers from freshwater studies that scored highest for quality

Location	Results reported (particles/L)	Sieve size (µm)	Study	Quality score (TAS)[a]
Groundwater, Germany	Average:[b] 0.7×10^{-3} Range:[b] $0 - 7 \times 10^{-3}$	3	Mintenig et al., 2019	14
Three Gorges Reservoir, China	Average: 4.7 Range: 1.6–12.6	48	Di and Wang, 2018	10
Dongting Lake and Hong Lake, China	Averages: 1.2 and 2.3 Ranges: 0.9–2.8 and 1.3–4.7	50	Wang et al., 2018	15
Wuhan, China	Range: 1.6–8.9	50	Wang et al., 2017	10
Rhine river, Switzerland, France, Germany, Netherlands	Average: 0.0056	300	Mani et al., 2015	10
Western Lake Superior, USA	Average: 0.00026	333	Hendrickson, Minor, and Schreiner, 2018	11

[a] TAS = total accumulated score, as reported in Koelmans et al. (2019). The maximum score is 18 and is calculated by adding scores for nine quality criteria, where for each criterion, a score of 0, 1 or 2 is assigned. See the annex for an overview of the nine quality criteria and for each study, the individual scores against each criteria. TAS values are underlined when all underlying scores are non-zero.

[b] These values include samples of groundwater and drinking-water derived from groundwater subject to further filtration.

A direct comparison of data between studies of fresh water and drinking-water, described below, cannot be made because in most cases freshwater studies targeted larger particles, using mesh sizes that were an order of magnitude larger than those used in drinking-water studies (see Box 2.3). Consequently, the small particles detected in drinking-water are not detected in most freshwater studies.

Box 2.3 Interpretation and comparison of occurrence studies

Interpretation and comparison of study results reporting microplastic particle numbers should be done with great care, as the studies often use different methods, including filter size and enumeration methods. This means some studies will not detect smaller sized particles at all or will characterize non-plastics as plastics.

2.6 Microplastic concentrations reported in drinking-water

A total of nine studies measured microplastics in drinking-water. Particle concentrations reported in individual samples ranged from 0 to over 10^4 particles/L and mean values ranged from roughly 10^{-3} particles/L in a study of drinking-water derived from groundwater to over 10^3 particles/L. In general, groundwaters are well protected from particulate contamination. Similarly, conventional drinking-water treatment is expected to provide an effective barrier for a wide range of particle sizes (see further information in section 5.3).

Different studies looked at different ranges of particle sizes and had different cut-offs for reporting particle sizes. Studies typically used a filter with a mesh or pore size of less than 10 µm and in some cases characterized particles as small as 1 µm. In the context of drinking-water, an arbitrary cut-off of 100 µm in length was suggested to distinguish large particle from small particles (Koelmans et al., 2019). Where studies looked at both large and small particles, small particles tended to be more numerous. Since there were so few studies, each is described in more detail in the annex. They are described in the annex in order of decreasing study quality, as determined by the TAS quantitative assessment, primarily from Koelmans et al. (2019). Some key results of the eight of the nine scored studies are summarized in Table 2.3. There was insufficient detail to fully assess the study quality of one of the studies, and therefore, is not summarized in the below table, but a short description is included in the annex for completeness.

Table 2.3 Summary of reported microplastic or microplastic-like particle numbers[a] and particle characteristics from drinking-water studies

Author	Water type	Lower size bound (µm)	Particles/L in sample (average)	Particles/L in blanks (average)
Oßmann et al. (2018)	Bottled (mineral water) • Glass • Single use PET • Reusable PET	1	 3074–6292 2649 4889	384
Pivokonsky et al. (2018)	DWTP from surface water sources (3 sites)	1	628 338 369	< 5% of counts in samples
Schymanski et al. (2018)	Bottled • Single use • Returnable • Glass • Beverage carton	5–20	 14 118 50 11	14 ± 13
Mason, Welch and Neratko (2018)	Bottled	6.5–100 lower bound based on microscope and software	315	23.5
Strand et al. (2018)	Tap from ground-water sources	10–100	0.2, 0.8 and 0.0 (LoD = 0.3)[d]	Unknown
Mintenig et al. (2019)	Tap from ground-water sources	20	0.0007	0.67 particles/L 0.3 fibres/L
Uhl, Eftekhardadkhah, and Svendsen (2018)	Tap form 24 sources	60	Average not reported since only a single result above LoQ (that result was 5.5)	0.5 (LoQ = 4.1 LoD[d] = 0.9)
Mason, Welch and Neratko (2018)	Bottled	>100	10.4	4.15
Strand et al. (2018)	Tap from ground-water sources	>100 (10 µm sieve size)	0.312 (LoD = 0.58)	0.26
Kosuth, Mason and Wattenberg (2018)	Tap from unspecified sources	100 lowest reported	5.45	0.33 (based on 5 particles in 30 blanks (ea. 500 mL)

[a] For details on whether particles identified were confirmed to be microplastics, see summaries of the individual studies in the annex.

[b] TAS = total accumulated score. The maximum score is 18 and is calculated by adding scores for nine quality criteria; for each criterion, a score of 0, 1 or 2 is assigned. TAS values are underlined when all underlying scores are non-zero.

[c] While the Mintenig et al. study was the highest rated study, the Mason et al. study was the only drinking-water study that had a non-zero score in all key quality criteria. Aside from Strand et al. and Uhl et al., the reported TAS values are from Koelmans et al. (2019). Strand et al. and Uhl et al. were assessed separately by one of the authors of the Koelmans et al. (2019) publication. See the annex for an overview of the individual scores against each quality criteria, including scores for Strand et al. and Uhl et al.

[d] LoD/LoQ = Limit of detection/Limit of quantification.

	Particle size (µm)	Predominant particle shape	Predominant polymer type	Quality score (TAS)[b, c]	Author
	Most particles smaller than 5 (>75% in glass and >95% in plastic bottles)	No discussion of shapes	PET in plastic bottles, PE, and styrene butadiene copolymer in glass	13	Oßmann et al. (2018)
	Most particles were in 1–10 range (up to 95%)	Fragments closely followed by fibres	PET but also PP, PE, polyacrylamide	11	Pivokonsky et al. (2018)
	40–50% in 5–10 range; over 80% <20	No discussion on shape; described as fragments	PET but also PP, PE	14	Schymanski et al. (2018)
	Not specified		No characterization	14	Mason, Welch and Neratko (2018)
	Mainly 20–100	Fragments	PET, PP, PS, acrylonitrile butadiene styrene, PUR	14	Strand et al. (2018)
	In the range 50–150	Fragments	Polyester, PVC, PE, PA, epoxy resin	15	Mintenig et al. (2019)
	Not specified	Not specified	No characterization	9	Uhl, Eftekhardadkhah, and Svendsen (2018)
	Not specified	Fragments (66%), fibres (13%), films (12%)	PP (54%)	14	Mason, Welch and Neratko (2018)
	Not specified	Fibres (82%), fragments (14%), films (4%)	PET, PP, PS	14	Strand et al. (2018)
	Fibre lengths 100–5000	Mainly fibres (98.3%)	No characterization	8	Kosuth, Mason and Wattenberg (2018)

2.7 Particle size, shape and polymer type in fresh water and drinking-water

Size, shape and polymer type are characteristics of microplastics that may influence how they are transported in water and may have implications for toxicity and efficacy of drinking-water treatment. Below is a brief summary of the characteristics of microplastic particles found in freshwater and drinking-water samples. For a detailed overview, see Koelmans et al. (2019).

The smallest particle sizes measured in fresh water are determined by the mesh size of the trawl net, which is typically 300 µm, although a few studies have been conducted with finer meshes. Higher particle counts tend to be reported when smaller particles are measured (Koelmans et al., 2019). Based on current analytical capabilities, particle sizes measured in drinking-water can be as low as 1 µm. This does not imply that particles smaller than 1 µm are not in drinking-water, rather detection is limited by currently available methods.

In freshwater studies, the shape of particles varied widely, with fragments, fibres, film, foam and pellets being the shapes most often reported (Koelmans et al., 2019). Fragments and fibres were the predominant particle types found in drinking-water. However, as stated by the authors, this data on shapes should be interpreted with caution, as they represent only a subset of isolated particles, which may or may not represent all particles. Also, each study focused on specific sizes and defined ambiguous shapes differently such as nurdle, pellet, pre-production pellet, resin or granule, making it difficult to compare across studies. Studies also differed in the extent to which their water samples represented the studied water systems or water type, which varied over space and time.

PP, PE, PS, PVC and PET were the polymers detected most frequently, an order that agrees roughly with production volumes. As described above, in addition to the production volume, polymer density is a key factor in determining which particles might be detected in studies that sample the upper layer of water. In bottled water, there is some evidence that microplastic occurrence appears to be at least partially attributable to the bottling process and/or packaging.

2.8 Other routes of exposure

Since plastics are so widely used in society, the public will be frequently exposed to plastics and potentially to microplastics. This includes direct exposure, whereby any plastic item placed in the mouth may expose a person to microplastics by abrasion.

Small children may potentially have increased exposure given the number of plastic toys and cups and cutlery made for children, and given oral exploration is a normal stage of child development. Everyday use of household objects (e.g. plastic cutlery, toothbrushes, cutting boards, cups, etc.) may also be sources of exposure. However, given there are no data on such exposures, this section focuses on food and air.

2.8.1 Food

In 2016, the European Food Safety Authority (EFSA) conducted a comprehensive review of existing data on microplastics in food. Nanoplastics were included within the scope of the EFSA review, but no occurrence data were available. Of the 13 studies cited, 10 measured microplastic concentrations in marine fish and shellfish. Typical concentrations of microplastics were single-digit particles per fish ranging up to 7 particles per fish and up to 10 particles/g of shellfish. Particle sizes in fish ranged from 130–5000 µm. Particle sizes found in shellfish were typically in the ranges 5–25 µm and 20–90 µm, although in some cases, longer fibres up to 4700 µm were reported (FAO, 2017). One study looked at microplastic concentrations in honey, reporting 0.166 fibres/g (range 40–9000 µm) and 0.009 fragments/g (range 10–20 µm). Another study analysed beer, reporting 0.025 fibres/mL and 0.033 fragments/mL (sizes not stated). Particles found in honey and beer were not spectroscopically confirmed. Another study examined salt, finding the highest concentration of microplastics in sea salt, at 0.550–0.681 particles/g (size 45–4300 µm).

Because mussels contained the highest median value of 4 microplastic particles/g and since they are eaten without removing their digestive tract, mussels represent a conservative microplastic exposure scenario for all fish and other seafood. Assuming the microplastic particles were 25 µm diameter with a density of 0.92 g/cm^3, EFSA estimated an intake of 7 µg of microplastics based on a 225 g portion of mussels. Based on intake at the highest concentration of sorbed contaminants or additives in the plastics and complete release from the particles upon ingestion, EFSA estimated that this scenario would result in very small increases in intakes of polychlorinated biphenyls (PCBs) (<0.006% increase), polycyclic aromatic hydrocarbons (PAHs) (<0.004% increase) and bisphenol A (BPA) (about 2% increase). The Food and Agriculture Organization of the United Nations (FAO) (2017) reached a similar conclusion for PCBs, PAHs, dichlorodiphenyltrichloroethane (DDT), BPA and polybrominated diphenyl ethers (PBDEs) considering the highest concentration of contaminants or additives in microplastics and the same worst-case microplastic intake assumption applied by EFSA. Note that systematic quality assessments for studies reporting microplastic concentrations in food and air have not yet been conducted, aside from seafood as reported in Hermsen et al., 2018.

2.8.2 Air

Limited data are available on levels of microplastics in air. Thus, the sources and transport mechanisms of microplastics in air remain poorly understood. A potentially important source of fine microplastic particulates to the atmosphere could be associated with tyre and road-wear particles. A recent study investigating the contributions of polymeric materials originating from tyre and road-wear particles, however, reported an average contribution of only 0.27% of fine particulate matter (PM2.5) in London, Los Angeles and Tokyo (Panko et al., 2019). Sea salt aerosol formation, wind-driven release of wastewater sludge, degradation of plastic sheeting and other construction materials, clothes drying, and wear and tear of textiles are all possible sources of airborne microplastics (Wright and Kelly, 2017). High concentrations of microplastics have been reported in occupational settings (SAPEA, 2019) and some data from domestic settings are outlined below.

Dris et al. (2016) monitored microplastics in total atmospheric fallout at two sites in Paris. Fibres accounted for almost all of the material collected, the remainder being a few plastic fragments (<100 µm in size). Atmospheric fallout of between 2 and 355 fibres/m^2/day was calculated from experimental data. Total atmospheric fallout during wet weather periods was substantially larger than during dry periods but a statistically significant correlation was not found. The predominant fibres were 200–600 µm in length and 7–15 µm in diameter. FTIR of a subsample confirmed that 50% of the total fibres were natural (mainly wool and cotton) and 21% were manufactured by transformation of natural polymers (rayon or acetate from cellulose). The remaining 29% contained at least some purely synthetic fibres, mainly PET and some PA. The lower size limit of the analysis was 50 µm.

Dris et al. (2017) investigated the fibres present in indoor and outdoor air, as well as in indoor settled dust. Three indoor sites and one outdoor site in Paris were monitored. Overall, indoor concentrations ranged between 0.4 and 59.4 fibres/m^3 with a median value of 5.4 fibres/m^3. Outdoor concentrations were significantly lower, ranging between 0.3 and 1.5 fibres/m^3. The deposition rate of fibres in the indoor environments ranged between 1586 and 11 130 fibres/m^2/day. The nature of the fibres was similar to that observed in the previous study by the same authors (described above): 67% were made of natural materials while the remaining 33% of fibres contained petrochemicals with PP being predominant. A similar size distribution was determined for indoor air, outdoor air and dust fall, and the distribution was similar to total atmospheric fallout with fibre length between 50 µm (the observation lower limit) and 450 µm.

Catarino et al. (2018) compared the relative exposure from ingesting marine mussels with the level of exposure from household deposition during a meal. To estimate microplastic exposure from mussels, measurements in mussels of 3 particles/g (mostly fibres) were multiplied by average shellfish consumption in the UK to arrive at an exposure level of 123 microplastic particles/year/capita in the UK and up to 4620 particles/year/capita in countries with a higher shellfish consumption. To estimate microplastic concentrations that would accumulate on a dinner plate during a meal, deposition rates of between 1 and 5 fibres were measured over a small surface area (approximately 4 cm^2) for 20 or 40 minutes. This yielded deposition rates over an order of magnitude larger than those observed by Dris et al. (2017). A correction was then made for the abundance of microplastics in dust based on Dris et al. (2017). Estimated exposure to microplastics during a meal via dust fallout ranged from 13 731 to 68 415 particles/year/capita which was much larger than via mussel consumption (4620 particles/year/capita). It should be stressed that these estimates were made by extrapolating a small number of particles falling on a small surface area and so should be treated with some caution.

2.9 Conclusions and research needs

Microplastics are ubiquitous in the environment. They have been found in marine water, wastewater, fresh water, food, air and drinking-water, both bottled water and tap water. With the information available at this time, it is difficult to make a robust quantitative estimate on the relative contribution from difference sources.

Two of the main inputs of microplastics into fresh water are surface run-off and wastewater effluent, although better data are required to quantify both these and other inputs and associate them with more specific sources.

The quality and quantity of data varies across different water types. Data on the occurrence of microplastics in drinking-water are limited at present, with few reliable studies using different methods and tools to sample and analyse microplastic particles.

Methods of sampling and analysis are not always straightforward. Important factors to consider when conducting sampling and analysis are summarized in Box 2.2. Principal amongst these include the need to avoid or minimize contamination during sampling and analysis and to use field and laboratory blank samples for quality control. Another important factor is confirming the polymer identity of the microplastic particles.

A wide range of particle shapes and sizes are found in fresh water, and the smallest particles detected are often determined by the mesh size. Typically, studies using large mesh sizes will report lower particle counts than those using small mesh sizes. The frequency with which different plastic polymer types are found is consistent with production volumes and plastic density. Routine methods are currently not available to detect nanoplastics in environmental samples.

The results of studies need to be interpreted in the context of the methods used and associated quality assurance/quality control mechanisms. However, limited data on drinking-water have provided some initial results.

- Microplastics have been identified in drinking-water as small as 1 µm, based on the smallest particle size detected by current methods.
- Large particles occur less frequently than small particles.
- The predominant particle shapes are fragments and fibres.
- The predominant plastic types are PET and PP.
- In addition to fresh water being a potential source of microplastics in drinking-water, there is some evidence from the type of plastics found that some contamination may arise during treatment and distribution of tap water, and/or bottling of bottled water. More data are needed to confirm the contamination sources.

Research needs

The following research would clarify the occurrence of microplastics in drinking-water and freshwater sources:

- More data are needed on the occurrence of microplastics in drinking-water to assess human exposure from drinking-water adequately.
- Studies on occurrence of microplastics must use quality-assured methods to determine numbers, shapes, sizes, and composition of the particles found. They should identify whether the microplastics are coming from the freshwater environment or from the abstraction, treatment, distribution or bottling of drinking-water. Initially, this research should focus on drinking-water thought to be most at risk of particulate contamination.
- Drinking-water studies would be usefully supplemented by better data on fresh water that enable the freshwater inputs to be quantified and the major sources identified. This may require the development of reliable methods to track origins and identify sources.
- A set of standard methods is needed for sampling and analysing microplastics in drinking-water and fresh water.
- There is a significant knowledge gap in the understanding of nanoplastics in the aquatic environment. A first step to address this gap is to develop standard methods for sampling and analysing nanoplastics.

3. Possible human health risks associated with microplastics in drinking-water: particles and chemicals

3.1 Introduction

Microplastics can present several unique challenges for traditional human health risk assessment approaches. Microplastics are not single chemicals or well-characterized substances but are particles that vary in shape, size and composition. Plastic polymers are generally considered to be of low toxicity. Being insoluble, they are unlikely to be absorbed from the gastrointestinal (GI) tract and generally do not interact with biological matrices, although particle size may influence absorption and toxicity (i.e. smaller particles may represent a greater hazard). However, plastics can contain additives and unbound monomers, which may leach out either into the surrounding water environment prior to human consumption or potentially, into the GI tract to become bioavailable under some circumstances. Further, plastic particles can sorb chemicals from the environment, some of which are of toxicological concern. The potential hazards from microplastic particles and chemicals associated with microplastics are explored in this chapter along with an assessment of their potential risk to human health.

The next chapter (Chapter 4) explores the hazards and potential risks associated with plastics in the environment (see Box 3.1), including microplastics that can provide a surface for microorganisms to attach and colonize (known as biofilms) with some potential for pathogenic organisms to be part of this biofilm.

Box 3.1 Risk is a function of toxicity and exposure

The potential hazards associated with microplastics in drinking-water come in three forms: particles presenting a physical hazard; chemicals, including monomers, additives and sorbed substances; and biofilms. Chapters 3 and 4 provide an assessment of these potential hazards along with an assessment of risk, which is a function of both toxicity and exposure. The same substance can have different effects at different doses, which depends on how much of the substance a person is exposed to and may also depend on the route by which the exposure occurs, e.g. ingestion, inhalation or injection. Consequently, the potential toxicity of these substances does not necessarily equate to risk in drinking-water. Similarly, the potential presence of a chemical, or release from plastic, does not in itself imply a risk to human health. Chemical risks are explored more thoroughly than other risks because there are more data available to inform risk scenarios.

3.2 Potential hazards associated with particles

Humans routinely ingest many different kinds of particles consisting of a variety of substances. Toxicity posed by particles is dependent on a wide range of physical properties that include size, surface area, morphology (shape), and surface characteristics. Toxicity can also depend on the chemical composition of the particles (discussed in section 3.3). Although toxicity is relatively well studied for inhaled particles, the toxicity of ingested particles is less understood. The fate and transport of particles following ingestion, particularly in the context of physicochemical properties, is not well studied. However, it is likely humans have ingested plastic particles for decades as a result of widespread contact with plastics in household objects including cutting boards, food packaging, and direct contamination in air and food.

When considering potential hazards from exposure to plastic particles, the actual particle component of the substance (i.e. physical hazard) and implications for toxicity and kinetics with oral exposure need to be assessed.

3.2.1 Toxicological data on microplastic particles

To date, most toxicological tests of microplastics have focused on aquatic organisms or ecotoxicology. No epidemiological or human studies on ingested microplastics have been identified. Data from studies on laboratory animals are scant and inadequate to inform human health risk assessment of microplastics ingestion. The current database of information on plastic particle toxicity (and absorption) is limited to a few studies using PET, PS or PE, and there are questions regarding the reliability of some of these studies, which are briefly described below.

In an OECD-compliant 90-day dietary study, no treatment-related adverse effects on blood parameters, organ weights or histopathology (including liver, a potential target organ) as well as mutagenicity, were seen when finely ground PET powder was mixed into the diet of 10 Sprague-Dawley rats per sex and dosed at 0, 0.5, 2.5 or 5% (Merksi et al., 2008). Particle sizes and counts were not reported, although particles were likely in the range of 1 to 50 µm (Welle and Franz, 2018). Although the study authors did not identify a no-observed-adverse-effect level (NOAEL) based on the reported results, the NOAEL can be considered the highest dose, equivalent to approximately 2500 mg/kg body weight (bw)/day, assuming a default 5% food factor for rats.

In non-standard studies in mice, liver effects reported by Deng et al. (2017) are considered with caution due to notable limitations in study design, data reporting and biological plausibility of results (Böhmert, Stock and Braeuning, 2019; Braeuning, 2019). Briefly, five mice per group that were exposed to high concentrations of PS particles

(mixture of 5 x 10^6 particles of 5 µm and 1 x 10^5 particles of 20 µm at 0.5 mg/day for 28 days via gavage) exhibited hepatic inflammation and lipid droplets at this highest dose tested, a dose selected as being five-fold higher than environmental exposures (Deng et al., 2017). However, incidence or severity data were not reported and effects on biochemical or molecular endpoints from this study have unclear functional or biological relevance. Male mice exposed to very high concentrations of PS particles (1.5 x 10^{10} particles/L of 0.5 µm at 100 or 1000 µg/L or 1.5 x 10^4 particles/L of 50 µm at 100 or 1000 µg/L in drinking-water for 5 weeks) had altered lipid metabolism and gut microbiota compared to controls (Lu et al., 2018). Another study in the same laboratory associated the altered gut microbiota, intestinal mucus secretion, and barrier function to the presence of 5 µm PS particles in the gut after these high exposures (1.5 x 10^6 particles/L at 100 µg/L or 1.5 x 10^7 particles/L at 1000 µg/L in drinking-water for 6 weeks) (Jin et al., 2019). The relevance of these high exposure scenarios where effects were reported in non-standard studies to human drinking-water exposures, as described in section 2.6, is questionable.

In the single identified study that evaluated oral toxicity of nanoplastics in a mammalian test species, no effects on body weight or on a battery of neurobehavioral tests were seen in adult male Wistar rats administered PS nanoplastics (mixture of 25 and 50 nm, average hydrodynamic diameter of 38.92 nm) via gavage at 0, 1, 3, 6, or 10 mg/kg bw/day for 5 weeks (particle count not reported) (Rafiee et al., 2018).

A co-exposure study with PE or PS microplastics (2000 µg/L) and organophosphorus flame retardants for 90 days in drinking-water (Deng et al., 2018) was not reviewed further due to the very high microplastic exposure and the inability to assess the individual contributions of PE, PS or the flame retardants to the observed effects.

In vitro assays in human cell lines were limited to a study in which PS and PE microplastics in two human cell lines showed oxidative stress for PS but not for PE and only at the highest concentration of 10 mg/L (Schirinzi et al., 2017), a very high concentration of unclear relevance to in vivo exposures. No effects were seen at the lower concentrations of 0.05, 0.1 or 1 mg/L. The limited number of identified in vitro and/or non-mammalian studies were not reviewed further due to limited relevance to the present human health effects assessment.

Studies on the release of plastic particles from surgical materials, such as prostheses, are of limited utility to inform possible health effects of microplastics (FAO, 2017; US EPA 2017). These studies have reported changes in gene expression, DNA damage, oxidative stress, cellular proliferation, tissue necrosis and inflammation but represent a very different exposure scenario from that of ingested microplastics in drinking-water and the relevance of these findings is highly uncertain.

There have been some studies that examined the effects of occupational exposure in the polymer industry and also exposure in non-occupational settings from indoor air caused by inhalation of polymer particles (Wright and Kelly, 2017; SAPEA, 2019). However, these exposure scenarios have unclear relevance to exposure through drinking-water.

3.2.2 Microplastic and nanoplastic uptake and kinetics

To assess possible risks associated with ingestion of plastic particles, it is important to understand how the particles will behave within the human body, and especially whether there is uptake in the GI tract. Uptake kinetics for microplastics and nanoplastics have been examined by the FAO (2017) and the EFSA Panel on Contaminants in the Food Chain (EFSA, 2016). Based on limited data and biological assumptions discussed below, the EFSA panel concluded that the largest fraction of ingested microplastics (>90%) was not likely to be absorbed and likely to be excreted directly through faeces, that microplastics >150 µm were likely not absorbed and that uptake of smaller microplastics was expected to be limited (i.e. ≤0.3%). Similar conclusions based on similar assumptions were reached by FAO, including unlikely absorption for microplastics >150 µm and limited overall absorption and uptake into organs for particles <20 µm. It is possible that absorption and distribution may be more significant for nanoplastics than microplastics (up to 0.3% for microplastics <150 µm and up to 7% for nanoplastics <0.1 µm) (FAO, 2017). However, EFSA (2016) and FAO (2017) both caution against extrapolations from the limited data available on only one type of nanoplastic.

EFSA and FAO conclusions are based on several studies including one in which uptake of 2 µm latex particles by rodents was reported as 0.04–0.3% (Carr et al., 2012) and another in which uptake of 3 µm polylactide-co-glycolide in mounted human colon tissue was approximately 0.2% for healthy individuals and 0.45% for tissues of patients with inflammatory bowel disease (Schmidt et al., 2013). The size threshold of <150 µm was selected based on limited data suggesting that particles in this size range possibly translocate from the gut into the lymphatic system (Hussain, Jaitley and Florence, 2001) and based on the translocation of PVC particles up to 110 µm to the portal vein of dogs (Volkheimer, 1975). Furthermore, particles >130 µm cannot cross the epithelium through persorption mechanisms. A recent study reported in the FAO document but not employed to draw conclusions examined uptake and distribution of fluorescent PS microplastics (1.46×10^6 particles/L of 5 µm and 2.27×10^4 particles/L of 20 µm) that were orally administered to mice over 4 weeks. Translocation to the liver and kidney reportedly occurred and particles could be detected 1 week after cessation of exposure (Deng et al., 2017). However, the plausibility of this study has been criticized due to inconsistencies related to analytical and mathematical methods used to estimate

target organ burdens (Böhmert, Stock and Braeuning, 2019; Braeuning, 2019). Before any indications of possible absorption or adverse effects can be inferred, the results need to be replicated after the methodological limitations are resolved.

Nanoplastic absorption may be potentially higher than their larger microplastic counterparts; however, the database is even more limited. Uptake of nanoscale (i.e. <0.1 µm) PS ranged from 0.2–7% in in vivo studies in rats (Jani et al., 1990; Walczak et al., 2015a) and 1.5–10% in in vitro studies (des Rieux et al., 2007; Kulkarni and Feng, 2013; Walczak et al., 2015b) (presented in EFSA, 2016); the rest was eliminated with faeces as unabsorbed material.

3.2.3 Information from broader particle toxicology

Potential effects in the gut

As noted above, most microplastics ingested via drinking-water are expected to pass through the GI tract without being absorbed. However, because the gut is the primary tissue that will come into contact with ingested particles, it has been identified as the tissue most likely to show effects. Oral exposure to particles in general, albeit at very high levels, has been associated with mild intestinal irritation and inflammation. There is speculation based on inferences from other particles (e.g. titanium dioxide and aluminosilicates) that plastic particles could accumulate in phagocytes of gut tissue (Wright and Kelly, 2017). While accumulation in phagocytes could potentially interfere with their function and compromise lymphocyte detection of infections and impair local immunity, this interference remains to be established. PS particles (1.5×10^{10} particles/L of 0.5 µm or 1.5×10^{4} particles/L of 50 µm) were also shown to alter the gut microbiome in mice exposed to high doses of 100 and 1000 µg/L through drinking-water for 5 weeks (Lu et al., 2018). Chickens exposed to 50 or 200 nm carboxylated PS nanoparticles at high doses (2 mg/kg bw/day for 2 weeks) showed increased iron uptake, suggesting that exposure to nanoplastics may affect the barrier properties of the gut epithelium (Mahler et al., 2012). Particle counts were 2×10^{13} particles/L of 50 nm or 1.25×10^{12} particles/L of 200 nm. Given significant inter-species variations in the microbiome, the relevance of these findings to humans needs to be investigated further before drawing any firm conclusions.

Particle properties and potential toxicity

The size and concentration of microplastic particles may influence their potential for toxic effects. As noted in section 3.2.2, smaller particles are more likely to cross the gut wall and reach other tissues. Moreover, as particle size decreases, its surface-area-to-volume ratio increases, which may make smaller particles more susceptible to adsorbing biologically-significant proteins and molecules. Furthermore, in the environment, the increased particle surface-area-to-volume ratio theoretically increases

the sorption capacity of environmental chemicals relative to particle weight. An increased surface-area-to-volume ratio also means that microplastics degrade faster than larger plastic particles (Gewert, Plassmann and MacLeod, 2015), although it is not clear if conditions in the human GI tract are amenable to plastic degradation. One study has shown that Antarctic krill can fragment PE particles of 31.5 µm to pieces smaller than 1 µm (Dawson et al., 2018), thus suggesting the potential for microplastics to break down into smaller plastic particles within at least some biological systems. Particle count (concentration) information is often not reported and may influence observed responses at higher concentrations by overwhelming biological mechanisms responsible for particle clearance.

Additional considerations including particle morphology and surface chemistry may play an important role in particle uptake and clearance in the lung (e.g. particularly evasion of clearance mechanisms), but how this relates to ingested plastic particles, which can occur in irregular shapes or as fibres, is less certain.

Aging plastics have been shown to form oxygen-containing functional groups on their surfaces. Therefore, weathered plastic particles may have different physicochemical properties including reduced hydrophobicity, which could reduce their ability to sorb hydrophobic substances (Endo, 2005) but increase potential for sorption of hydrophilic organic pollutants (Liu et al., 2019). Further, any particle with a diameter of less than 0.1 µm in any dimension, including nanoplastics, may exhibit physicochemical properties different from the bulk material (Khan, Saeed and Khan, 2017).

3.3 Potential hazards associated with monomers, additives and sorbed chemicals

3.3.1 Monomers

Polymerization reactions do not generally proceed to full completion, resulting in a small proportion of monomers that are free to leach from polymerization products. Residual monomer content can range from negligible to up to 4% depending on the type of polymer produced and polymerization technique used (Araújo et al., 2002; Lithner, Larsson and Dave, 2011). Biodegradation of plastics (e.g. by microorganisms on biofilms) and plastic weathering may also degrade plastic polymers into monomers and oligomers; however, the extent to which this occurs is uncertain. Should degradation occur, it should be noted that unbound monomers are likely to leach in the environment, resulting in extremely small concentrations in drinking-water sources and that many are not stable in water. For example, propylene oxide would convert to propylene glycol which has low toxicity (Trent, 2001).

Some monomers, such as acrylamide, 1,3-butadiene, ethylene oxide and vinyl chloride are considered more hazardous than others based on a hazard ranking approach for 61 monomers described in Lithner et al. (2011). The risk associated with these monomers varies significantly, depending on a number of factors, including the level and route of exposure. The WHO Guidelines for Drinking-water Quality (2017a) assessed six of these monomers and established guideline values for five substances (acrylamide, epichlorohydrin, 1,4-dichlorobenzene, styrene, and vinyl chloride) ranging from 0.3 (for vinyl chloride) to 300 µg/L (for 1,4-dichlorobenzene) (WHO, 2003d, e; 2004c, e; 2011a; 2017a). These guideline values generally represent concentrations in drinking-water that do not result in any significant health risk over a lifetime of consumption (WHO, 2017a). Of these, only vinyl chloride was assessed as a monomer associated with plastic, as it can be released from unplasticized PVC pipes. Acrylamide and epichlorohydrin were assessed in relation to coagulant aids and styrene, 1,4-dichlorobenzene and formaldehyde as pollutants or by-products of water treatment. Formaldehyde was also assessed but no formal guideline value was established, although a tolerable concentration was identified at 2.6 mg/L (WHO, 2005).

3.3.2 Additives

Additives are incorporated into plastics in various quantities to confer specific properties. In contrast to monomers, additives are not covalently bound to the polymer (with the exception of a few that are co-polymerized) and can thus leach into the surrounding environment (Hahladakis et al., 2018). Following the principles of thermodynamics, chemical additives will leach in a manner that enables them to reach a thermodynamic equilibrium with their surroundings, potentially resulting in chemical additives from microplastics being emitted to air, water and soil.

The molecular weight of additives may also influence their release into the environment. In general, small, low molecular weight molecules can migrate at a faster rate than larger additives. Substances with a molecular weight higher than 600 g/mol have a low tendency to migrate from plastic (Hansen et al., 2013). Migration may potentially increase as plastics age and weather, although this phenomenon is not well understood (Suhrhoff and Scholz-Böttcher, 2016; Jahnke et al., 2017).

There are no data to quantify the relative importance of microplastics in contributing to chemical additives in the environment, including drinking-water. However, relative to other emission routes of additives to the environment, it is anticipated that leaching from microplastic will be relatively small. Although some plastic additives, such as phthalates, PBDE and lead or cadmium-containing colorants, are considered hazardous at sufficient exposures, health-based values, regardless of source, have been established for many of these additives by international agencies.

There is limited information to support the possibility that microplastics act as a vector of transport for chemical additives. A study by Tanaka et al. (2015), for instance, reports the presence of deca PBDE in the stomach oil of seabirds as a result of plastic ingestion. Other studies, such as by Koelmans, Besseling and Foekema (2014), appear to question the relative importance that leaching of nonylphenol and BPA from microplastic plays as a source of contamination to lugworms and cod.

Many efforts have been taken to reduce the use of additives-of-concern from plastics (especially for phthalates, PBDEs, cadmium, lead and BPA). However, it is possible for these substances to be present in older plastics, which may degrade into micro- or nanoplastics in the environment.

3.3.3 Sorbed chemicals

The hydrophobic nature of microplastics implies that they have the potential to accumulate hydrophobic substances such as persistent organic pollutants (POPs), including PCBs, PAHs, and organochlorine pesticides. Indeed, the capacity of plastic polymers, such as PE and PUR, to accumulate POPs from the environment is a fundamental principle in their application as passive samplers used for environmental monitoring (Müller et al., 2001; Adams et al., 2007; Hale et al., 2010; Lohmann et al., 2012).

Observations reporting the concentration of POPs associated with microplastics have largely focused on the marine environment. Data from the literature spanning four decades have been reviewed in Wang et al. (2018), for instance, who report significantly higher concentrations of POPs in microplastics near populated urban areas, which is consistent with the relative level of contamination of the surrounding environment for these contaminants. In 2005, the International Pellet Watch was launched as a volunteer-based means of monitoring POPs on unintentionally released plastic particles collected on beaches around the world (Pellet Watch, 2019). Some information on reported concentrations of chemicals detected in microplastics, including some POPs, is included in Table 3.2.

In addition to accumulating in microplastics, it is well understood that POPs will indiscriminately sorb to organic carbon in the environment, such as that found in sediment, algae and the lipid fraction of biological organisms. Given the relative abundance of sediment, algae and aquatic organisms compared to microplastic particles in freshwater environments, the fraction of POPs sorbed to microplastics will be small compared to the other environmental media. Thus, the relative importance of microplastics to act as a vector of transport of POPs is likely to be negligible (Koelmans et al., 2016).

Should microplastics be ingested through drinking-water, the rate at which chemicals are released or taken up from microplastic in the GI tract will depend on interactions

between the chemical and the microplastic particle itself, as well as the properties of the surrounding environment (Karapanagioti and Werner, 2018). For instance, chemical uptake and release can be influenced by the size of the particles, whereby decreasing size increases the rate of uptake or loss (Lassen et al., 2015). In studies using a simulated gut fluid, the release of POPs, such as PCBs, can be observed whereby a relatively uncontaminated gut fluid and long residence time can result in significant chemical leaching. Alternatively, when the gut fluid already contains the chemical contaminant, the reverse process can be observed, with uptake into the plastic occurring (Mohamed Nor and Koelmans, 2019). Consequently, the relative potential for POPs to leach from microplastics will depend on a variety of factors, including the relative size of the particle, mass of chemical accumulated, relative level of contamination within the gut, and the GI residence time of the particle.

As it is well understood that POPs are associated with a variety of potentially adverse human health effects, health-based values have been established for many of them by international agencies. For example, WHO has developed a drinking-water guideline value for benzo(a)pyrene of 0.7 µg/L; this compound is associated with particles from old coal tar-lined water mains (WHO, 2003c).

3.4 Assessing possible risks from microplastics

In assessing the potential human health risks from exposure to microplastics in drinking-water, a first step is to consider the exposure from that source.

There is currently a paucity of information to quantitatively assess any potential risk associated with exposure to microplastic particles. Considerations related to certain risk aspects of particle exposure are discussed in section 3.4.1.

With respect to chemicals associated with microplastics, due to the limited data available, estimates of exposure are made using an extremely conservative approach described in section 3.4.2. This analysis provides a means for estimating upper-bound contributions of exposure to microplastics from drinking-water and represents the starting point in a tiered risk assessment. If there is no apparent risk in an extreme exposure scenario, then there is no need to refine the assumptions underpinning the exposure assessment unless and until more information becomes available that might contradict these assumptions.

To characterize the risk for chemicals associated with microplastics, the estimated exposure in drinking-water can be compared to conservative levels at which adverse biological effects could be observed (the toxicological point of departure, or POD) to determine if there is a sufficiently large margin of exposure.

3.4.1 Assessment of risk related to particle exposure

There is insufficient information to draw firm conclusions on potential risk associated with exposure to particles at this time. However, the polymers comprising microplastic particles are generally considered to be inert when ingested and the limited evidence on particle kinetics suggests that a large fraction of microplastics pass through the digestive system without uptake. Potential uptake of very small microplastic particles is a topic of emerging research interest. However, the limited studies that have investigated uptake of microplastic particles <50 µm in size lack methodological robustness and present findings only at extremely elevated exposure concentrations. Elevated levels of exposure to particles are likely to overwhelm biological mechanisms that would allow particle clearance, and therefore, there is no information of suitable quality to draw any conclusions on uptake of small particles at this time. It is unclear if absorption of small plastic particles in the GI tract, like other inert particulate matter to which humans are exposed to on a regular basis, would pose any human health concerns. As noted earlier, it is almost certain that humans have been exposed to microplastics for decades, as well as other particles in the environment for much longer. Overall, there does not seem to be any reliable information at this time that would suggest any overt health concerns associated with microplastic particles. This does not mean that plastic particles are a priori innocuous, as this cannot be determined with any accuracy at present with the limited data on microplastics in drinking-water. Consequently, assessing the potential hazards, exposure and thereby risk would benefit from studies that can identify those properties of microplastic particles that might represent a hazard and then develop methods aimed at assessing their exposure to enable a robust assessment of risk.

> Although there is insufficient information to draw firm conclusions on the toxicity related to the physical hazard of plastic particles, particularly the nano size particles, no reliable information suggests it is a concern through drinking-water exposure.

3.4.2 Assessment of risk related to chemical exposure

As described in section 3.3, microplastic particles can contain unreacted monomers and various additives, such as stabilizers and colourants, which may leach out in water or the GI tract. Regulatory systems for plastics in contact with food or water consider the leaching potential of these substances into environmental media as part of the approval process. While regulations do not directly relate to human consumption of plastic particles, they do constrain the additives and residual monomer content that can be included, which is particularly important for plastics in contact with drinking-water that could be a source of particles. However, many plastics not intended for

contact with food or water (which are likely to be a key source of microplastics in freshwater environments) will not have undergone such assessments and may contain unregulated substances and substances at potentially higher concentrations. There is also the potential for some microplastics in the environment to sorb substances that could be a concern at higher concentrations. To estimate potential human health risk, the first step in a tiered approach is to determine whether very high exposures to these potential hazards pose a risk to consumers.

3.4.2.1 Conservative Exposure Scenario

A scenario that would result in very high exposure to microplastics is presented below. This scenario is intended to represent an extreme case and in the absence of a more thorough understanding of the factors contributing to exposure, is likely to exaggerate probable exposure. Assumptions are made regarding the size, shape and density of the microplastic particle and the particle numbers in drinking-water. Table 3.1 lists all exposure assumptions and provides an indication of the level of conservativism of each. While it is important to remember that multiplying a series of theoretical extreme assumptions can lead to assumed situations that are well outside the realms of realistic exposure in the environment, or in this case drinking-water, it is a useful screening tool to indicate where the evaluation may need to be refined.

Considering the above assumptions on particle characteristics and a default consumption of 2 L of drinking-water/day (WHO, 2017a), an intake of 85 µg of microplastics/day can be estimated. This corresponds to an intake of 1.4 µg microplastics/kg bw/day based on a default body weight of 60 kg for an adult, which is considered to be extremely conservative and highly unlikely since it is based on a combination of extreme scenarios.

Applying the same assumptions to actual data on particle numbers and sizes reported by Kosuth, Mason and Wattenberg (2018), Oßmann et al. (2018), Pivokonsky et al. (2018) and Schymanski et al. (2018), more realistic estimated intakes would be around 2 µg/day or 0.03 µg/kg bw/day. Estimated intake based on data from Mintenig et al. (2019) on particle numbers and sizes is 0.01 µg/day. Welle and Franz (2018) estimated intakes ranging up to 8.7 µg/day. For the sake of comparison, EFSA (2016) estimated that a worst-case intake from seafood alone based on a 225 g portion of mussels would be 7 µg microplastic.

Table 3.1 Exposure assumptions to assess microplastic intake in drinking-water, along with rationale and associated level of conservatism

Parameter	Assumption	Rationale	Level of conservatism
Shape	Sphere	Sphere represents a larger volume compared to a fragment or a fibre. The most common descriptors of particles found in drinking-water were fragments or fibres.	Very high: a sphere of 150 µm diameter is about sixty-fold greater in volume than a fibre 150 µm long and 10 µm in diameter, resulting in higher amounts of monomers and additives.
Size (diameter)	150 µm[a]	The Mason, Welch and Neratko study (2018), which was considered one of the highest-quality studies (see section 2.6), characterized particles >100 µm but did not give an upper particle size. This is an extreme estimate and is consistent with the upper range of the Mintenig paper (2019), which was the highest rated study (see section 2.6). Particles of this size or greater are not likely to be absorbed in the body and would be removed by filtration in water treatment.	Extreme best estimate: a sphere of 150 µm diameter is three-fold larger in volume than a sphere of 100 µm diameter, resulting in higher amounts of monomers and additives.
Density	2.3 g/cm^3 Range of 0.9-2.3 (PP and PE, the most common polymers, have densities of 0.9-0.91 to 0.965-0.971, respectively.)	Highest reported polymer density (for polyester).	Very high: this is two-fold greater than a typical density of 1.
Particle numbers in water	10.4 particles/L[b]	The highest average number of spectroscopically confirmed large particles (>100 µm) from one of the highest quality studies[c].	Best estimate based on available data.

[a] Mintenig et al., 2019.

[b] Mason, Welch and Neratko, 2018 (average reported for particles > 100 µm).

[c] An assessment based on the number of identified small particles, that may or may not represent a significant fraction of microplastic particles, was also conducted (see section 3.4.2.2 for more information).

3.4.2.2 Margins of exposure assessment

When assessing risk of environmental chemicals, it is common to use a screening level margin of exposure (MOE) approach. Here, a toxicological POD, usually a NOAEL or a lower confidence limit on the benchmark dose (BMDL) from laboratory animal studies, is divided by the estimated human exposure to characterize potential health risks. MOEs of at least 100 when based on animal data and 10 when based on human data are an indication for low health concern for effects with an apparent threshold (FAO/WHO, 2009). For genotoxic carcinogens there is low health concern for compounds with an MOE above 10 000. Such defaults are considered adequately protective of a wide range of individuals within the population, particularly when combined with the elevated assumptions in the exposure assessment, as carried out here.

To calculate the MOE associated with microplastics in drinking-water, chemicals were included if:

- they have been detected in microplastics,
- are of toxicological concern, and
- have adequate or accepted toxicological PODs for deriving a MOE (on this basis, lead and per- and polyfluoroalkyl substances (PFAS) were excluded from the MOE approach).

In calculating the estimated daily intakes of chemicals associated with microplastics, the very conservative exposure assumptions as described in table 3.1 were maintained and additional exposure assumptions were added (see Table 3.2):

Table 3.2 Exposure assumptions to assess microplastic intake in drinking-water, along with rationale and associated level of conservatism

Parameter	Assumption	Rationale	Level of conservatism
Chemical concentrations in microplastic	Highest reported[a]	Upper-bound concentrations measured, although data are limited to marine microplastics.	High: concentrations often vary over several orders of magnitude and concentrations of contaminants in marine microplastics may be much higher than in fresh water since they will have longer to equilibrate. For some of the studies there was a three-fold difference in concentration between the highest and second highest value and more when compared with a mean.
Leaching/ bioavailability of the chemical contaminant in the body	100%	In the absence of information on leaching in the GI tract, complete release is assumed.	Very high: release from plastics is complex; more information on extraction with gut fluid would help refine this assumption.

[a] Highly variable. Data quality not assessed.

As shown in Table 3.3, MOE values derived in this risk assessment were adequately protective, indicating low health concern for exposure to chemicals in microplastics through ingestion of drinking-water. Margins of exposure were generally much greater than 100, and for the two genotoxic carcinogens (benzo(a)pyrene and hexachlorobenzene), were greater than 10 000.

Although the MOE values indicate a low health concern for human exposure to chemicals through ingestion of drinking-water containing microplastics at the levels detected in the available studies, there is significant uncertainty related to exposure to smaller plastic particles. One study by Mason, Welch and Neratko (2018) that investigated microplastics in bottled water measured 315 particles/L, for the size fraction of 6.5 to 100 µm (median particle size = 53.25 µm) that could be plastic. While there is some uncertainty whether these smaller particles are indeed plastic particles, an exposure scenario was also calculated using these assumptions of size and particle number. Changing these assumptions did not significantly impact the outcome of the preliminary risk calculation; MOEs were only 1.4-fold less than calculated using assumptions of 10.4 particles/L of 150 µm, and remained adequately protective for all chemicals. Applying assumptions with higher particle numbers in smaller size ranges would not change the conclusions.

MOE values derived in this risk assessment were adequately protective, indicating low health concern for exposure to chemicals in microplastics through ingestion of drinking-water. Applying assumptions with higher particle numbers in smaller size ranges would not change the conclusions.

Table 3.3 Upper-bound daily intake estimates of chemicals from microplastics, maximum levels of contaminants associated with microplastics, and corresponding MOE

Chemical[a]	Upper bound concentration in microplastic (µg/g)	Maximum daily intake (ng/kg bw/day)[b]	Point of departure (µg/kg bw/day)
Bisphenol A	0.7297	0.001	609
Cadmium	3390	5.0	0.8
Chlordane	0.0144	0.00002	50
Di(2-ethylhexyl)phthalate	0.0699	0.0001	2500
Dichlorodiphenyltrichloroethane	7.1	0.0001	1000
Hexachlorobenzene	0.0587	0.00002	50
Polyaromatic hydrocarbons	119	0.06	100
PBDEs	9.9	0.01	100
PCBs	18.7	0.03	5

[a] Comparison of maximum daily intakes for all substances to their respective WHO health-based drinking-water values also demonstrated a negligible contribution of these chemicals from microplastics in drinking-water. Contributions from benzo(a)pyrene (WHO, 2003c), chlordane (WHO, 2004a), DEHP (WHO, 2003b), DDT (WHO, 2004b), and hexachlorobenzene (WHO, 2004d) were well below 1%. Contribution of cadmium to the WHO guideline value (WHO, 2011b) is less than 5%. Lead was not considered in this risk assessment because WHO concluded that it was not appropriate to set a health-based guideline value for this metal; the provisional guideline value of 0.01 mg/L is based on practical achievability, where lead may be used in plumbing materials in buildings, including fittings, solders and pipes, as well as service connections to buildings (WHO, 2016). Lead stabilizers were used in unplasticized PVC water pipes but this has not been the case for decades. The highly conservative estimated maximum intake from microplastic particles for a child would be 0.025 µg/kg bw so this would equate to an intake of approximately 2% of the provisional guideline value and therefore of low concern.

[b] Maximum daily intake = maximum concentration in microplastic [µg/g] × mass of plastic particle [g] × particle concentration in water [particles/L] × daily drinking-water intake [L]/default body weight; where an adult is assumed to consume 2 L water/day, and default body weight is 60 kg (WHO, 2017a). The mass of a plastic particle is calculated as $4/3\pi r^3$ x density, where the radius is 75 µm, and density is 2.3 g/cm^3. As noted in section 3.4.2, the exposure assessment assumptions were highly conservative. Therefore, this estimated maximum daily intake is extremely improbable; actual intakes are likely to be significantly lower.

BPA: Maximum concentration is from marine microplastics (Hirai et al., 2011). POD is human equivalent dose from a lower 95% confidence limit on the benchmark dose for a 10% response ($BMDL_{10}$) based on kidney weight changes in mice (EFSA, 2015). A more recent draft report of an extensive study by the National Toxicology Program in the USA (2018) concluded that "BPA produced minimal effects that were distinguishable from background in this study, particularly below 25 mg/kg bw/day." This is greater than 25 times the POD used here. Because it is still in draft, the original value was retained, but it is probably highly conservative in comparison to the most recent data.

Cadmium: Maximum concentration is from the southwestern English shore (FAO, 2017; Massos and Turner, 2017). Note that cadmium-based pigments are now rarely used in plastics nor have cadmium compounds been used as stabilizers in plastics in contact with drinking-water. Cadmium is rarely detected in drinking-water above the WHO drinking-water guideline value of 3 µg/L; the MOE for cadmium is calculated using the POD corresponding to the 5th percentile level of calcium intake (as indicated by urinary biomonitoring marker for renal pathology) in an extensive human study in individuals aged 50 years or older (JECFA, 2011).

Chlordane: Maximum concentration is from a review of concentrations in marine microplastics (Nerland et al., 2014); POD is NOAEL from a long-term study in rats (WHO, 2004a).

DDT: Maximum concentration in marine microplastics is estimated from the sum of DDT congeners (Rios, Moore and Jones, 2007). Based on the information presented in Rios, Moore and Jones (2007), it is estimated that the concentration of DDT is 1.6 µg/g. Note that concentrations of DDT in the environment has decreased over time. POD is NOAEL for DDT based on developmental toxicity in rats (FAO/WHO, 2001). Therefore, the estimated MOE is likely to be conservative.

DEHP: Maximum concentration is from the coastal beaches of North China (Zhang et al., 2018). DEHP is primarily used in PVC and can account for 10–40% of PVC; POD is NOAEL based on liver peroxisome proliferation in rats (WHO, 2003b).

Hexachlorobenzene: Maximum concentration is from marine microplastics from the coastal beaches of Brazil (Taniguchi et al., 2016). POD is NOAEL from hepatic effects in pigs and rats (IPCS, 1997). Tumorigenic dose associated with a 5% incidence for tumours (TD_5) for neoplastic effects is also available, but provides a larger MOE.

PAHs: Maximum concentration is the sum of 16 PAHs in marine microplastics in China (Mai et al., 2018). Benzo(a)pyrene, the most thoroughly studied and highly potent PAH has low solubility and has been rarely detected in drinking-water at concentrations above 10 ng/L; POD is $BMDL_{10}$ for benzo(a)pyrene-induced forestomach and lung tumors in mice (JECFA, 2006b).

PBDEs: Maximum concentration is the sum of 20 PBDEs from marine microplastics (Hirai et al., 2011). The limited toxicity data suggested that for the more toxic PBDE congeners, adverse effects would unlikely occur in rodents at doses of less than 100 µg/kg bw/day. POD as cited by the Joint FAO/WHO Expert Committee on Food Additives (JECFA 2006a) is conservative compared to more recent assessments by other agencies.

PCBs: Maximum concentration is from marine microplastics in Japan (Endo, 2005). POD is lowest-observed-adverse-effect level (LOAEL) for decreased immune response in monkeys (IPCS, 2003).

Margin of exposure (MOE)	Adequacy of MOE	Conclusion	Chemical
5.9×10^8	MOE of at least 100	No safety concern	Bisphenol A
1.7×10^2	MOE of at least 10[c]	No safety concern	Cadmium
2.5×10^9	MOE of at least 100	No safety concern	Chlordane
2.5×10^{10}	MOE of at least 100	No safety concern	Di(2-ethylhexyl)phthalate
1.0×10^8	MOE of at least 100	No safety concern	Dichlorodiphenyltrichloroethane
6.0×10^8	MOE of at least 100	No safety concern	Hexachlorobenzene
6.0×10^5	MOE of at least 10 000	No safety concern	Polyaromatic hydrocarbons
7.2×10^6	MOE of at least 100	No safety concern	PBDEs
1.9×10^5	MOE of at least 1000[d]	No safety concern	PCBs

[c] The adequacy of the MOE for cadmium is assessed against a value of 10 as the POD is based on human data and accounted for intra-individual variation in toxicokinetics and toxicodynamics.

[d] The adequacy of the MOE for PCBs is assessed against a value of 1000 instead of 100 to account for use of a LOEAL instead of a NOAEL as the POD.

3.5 Conclusions and research needs

Investigation of potential risks related to particles indicate that it is possible that some smaller plastic particles may be able to pass through the gut wall and translocate to tissues remote from the mucosa, although this may not necessarily translate to a health risk. Humans have always ingested particles and have ingested plastic particles for decades with no related indication of adverse health effects. In addition, a good deal of evidence suggests that microplastics pass through the GI tract into the faeces. The health effects database of plastic particles is limited to a few studies. Although there are some data of questionable quality to suggest limited uptake of microplastics <50 μm in the GI tract in laboratory animals at high concentrations, the data require confirmation under realistic exposure scenarios. The evidence presented by these studies does not indicate whether there are risks relating to the physical hazard of plastic particles. Therefore, it is not possible to draw any firm conclusions on toxicity related to microplastic exposure through drinking-water, particularly for the smallest particles, but no reliable information suggests it is a concern.

With respect to chemicals, a very conservative exposure scenario and MOE assessment indicates low concern for human health.

Research needs

In order to conduct a more robust human health risk assessment of microplastics, the following data gaps should be addressed:

- There is a need to better understand occurrence of microplastics in drinking-water, as described in Chapter 2, based on high quality and quality-assured detection and enumeration methods. Studies should include nanoplastics when standard methods are available.
- More research is needed to understand the uptake and fate of microplastics in the GI tract and the influence of particle size, shape and chemical composition, particularly in relation to the smallest particles.
- Quality-assured toxicological data from cell models and/or experimental animals are needed for the most common forms of plastic particles that are appropriate for human health risk assessment.
- More knowledge is needed on the characteristics of plastic particles that are most predictive of their toxicity.
- A better understanding of the bioavailability of chemical substances associated with microplastics within the GI tract and other organs would be helpful to refine the exposure assessment.

4. Possible human health risks associated with microplastics in drinking-water: biofilms

4.1 Introduction

Biofilms in drinking-water are the result of the growth of microorganisms on drinking-water pipes and other surfaces (WHO, 2014). In drinking-water distribution systems, biofilms can detach from the pipe walls into the water, representing a source of the background numbers of heterotrophic bacteria that are found in all drinking-water. Although most microorganisms found in biofilms are believed to be primarily non-pathogenic, some biofilms can include free-living microorganisms and opportunistic pathogens such as *Pseudomonas aeruginosa*, *Legionella* spp., non-tuberculosis *Mycobacterium* spp. and *Naegleria fowleri*. In contrast, obligate enteric pathogens can be harboured within biofilms but generally do not multiply outside host organisms.

The characterization of biofilms and their related health risks from distribution systems are described in the Guidelines for Drinking-water Quality (WHO, 2017a) and in the Water Safety in Distribution Systems document (WHO, 2014). However, little is known about the presence of microplastic-associated biofilms in drinking-water and whether there are any related possible human health risks. Since the surface area of plastic particles is dwarfed by the surface area of drinking-water distribution and premise plumbing systems, the potential risk of biofilms associated with microplastics is considered far lower than for biofilms associated with drinking-water distribution systems. Nevertheless, this chapter discusses the hazards and potential risks associated with biofilms that may attach to and colonize microplastics and find their way into drinking-water or drinking-water sources.

4.2 Characteristics of plastics and microorganisms that influence biofilm formation

Materials of many sorts, including microplastics, provide a surface for biofilm-forming organisms to attach and colonize in aquatic environments. These plastic-associated communities are sometimes referred to as "plastispheres" (Zettler, Mincer and Amaral-Zettler, 2013). Several physical, chemical and biological factors have been identified that influence the formation of plastispheres, mostly in marine environments. Surface roughness of synthetic polymers promotes biofilm formation (Pedersen, 1990, Rogers et al., 1994; Nauendorf et al., 2016), while physicochemical properties drive the

attachment process. Biofilm-forming organisms attach faster to hydrophobic nonpolar surfaces, such as plastics, than to hydrophilic surfaces, such as stainless steel (Rummel et al., 2017). Gene sequencing analysis have shown that bacteria assemble differently on microplastics and have lower taxon richness, diversity and evenness on plastic than on non-plastic substrates (McCormick et al., 2016). Plastic surface properties influence the composition of the plastisphere community, as noted with biofilms on plastic versus non-plastic pipes used to convey drinking-water (Buse et al., 2014; van der Kooij et al., 2017). For example, most bacterial and fungal strains found on plastic were those able to degrade plastic polymers such as various species within *Pseudomonas*, *Arcobacter*, *Erythrobacter*, *Streptococcus*, *Staphylococcus*, *Aspergillus*, *Penicillium*, and *Phanerochaete* (Bhardwaj, Gupta and Tiwari, 2012; McCormick et al., 2014).

Biological characteristics of biofilm-forming organisms also influence their attachment to plastic surfaces including microplastics. Adaptation strategies, including hydrophobicity of cell walls and repulsive/attractive interactions between the surfaces of biofilm-forming organisms and the surrounding medium, promote attachment (Rummel et al., 2017). Moreover, environmental conditions, including high nutrient concentrations (nitrogen and phosphorus), salinity, temperature, high UV radiation and oxygen content are also factors influencing plastics and microplastics-biofilm formation (Harrison et al., 2018; Oberbeckmann, Kreikemeyer and Labrenz, 2018).

4.3 Potential concerns associated with microplastic-associated biofilms in water

The possibility that microplastics could act as vectors for the long-distance transport of pathogens and increased transfer of antimicrobial resistance has been raised based on a limited number of occurrence studies in fresh water.

4.3.1 Long-distance transport of pathogens

Although limited, current evidence suggests that microplastics may be able to transport and disperse plastisphere communities over long distances. For example, microplastics released from WWTPs may enable transport of sewage-related microorganisms in the effluent for long distances (McCormick et al. 2016; Oberbeckmann, Kreikemeyer, and Labrenz, 2018). Microplastics may also serve as vectors for harmful organisms, including enteric viruses and protozoa, as these organisms can accumulate in biofilms, harbour other pathogens and remain infectious in the plastisphere (Atanasova et al., 2018; Sun et al., 2018). A study conducted in nine rivers in Illinois, USA, found higher presence of *Pseudomonas* spp., *Burkholderiales incertae sedis*, and *Campylobacteraceae* on microplastics than on other suspended matter or in water (McCormick et al., 2016).

However, the increased abundance of *Campylobacteraceae* on microplastics was not significant. *Pseudomonas* spp. have been associated with degradation of plastic polymers; *Burkholderiales incertae sedis* are commonly found in wastewater treatment systems; and *Campylobacteraceae* include pathogenic species that are common in sewage and can cause a range of infections if ingested in contaminated drinking-water (WHO, 2017a). Although sewage-related pathogens can attach to microplastics and may be transported downstream of WWTPs, it is unclear how long they will persist, as obligate pathogens such as *Campylobacter* will not multiply in biofilms.

The issue of plastic-mediated transport of pathogens should not be overestimated as there are significantly greater sources of opportunist and obligate pathogens in surface waters used as sources of drinking-water. In addition, drinking-water treatment can remove most of these plastic particles (see section 5.3).

4.3.2 Antimicrobial resistance

A series of laboratory studies using lake water found that antimicrobial-resistant strains that attach to biofilms on microplastics transfer antimicrobial-resistant genes more frequently and to a broader range of species than free-living bacteria or biofilms associated with natural aggregates (Arias-Andres et al., 2018). The authors of these studies hypothesized that the high density and close physical contact between cells of biofilms could facilitate the transfer of plasmids with antimicrobial-resistant genes. Similarly, Eckert et al. (2018) showed that attachment to microplastic could favour bacterial survival from WWTPs, including genes associated with antibiotic resistance. The possibility that pathogens could invade new localities, and natural, non-pathogenic microorganisms could potentially acquire and spread antimicrobial resistance genes are issues of concern that need to be further studied. However, to contextualize the issue, biofilms in WWTPs carry a much greater density of organisms carrying resistance than do biofilms on microplastics.

4.4 Distribution and risk of microplastic-associated biofilms in drinking-water

To date, there are limited data on the distribution of microplastic-associated biofilms in drinking-water. Further, current knowledge on the adverse effects of microplastic-associated biofilms in fresh water and drinking-water is limited (US EPA, 2016; Li, Liu and Chen, 2018).

Although microplastic-associated biofilms have been detected in fresh water, their presence does not necessarily translate to occurrence and risk in drinking-water and there is currently no evidence to suggest a human health risk from microplastic-

associated biofilms in drinking-water. As part of drinking-water treatment, clarification and membrane processes represent effective methods to remove particles with attached microorganisms (see section 5.3) and disinfectants should inactivate biofilms. As discussed in section 2.2.7, there is evidence that small numbers of microplastics can slough from materials within water treatment and distribution systems. The surface area of these particles and associated biofilms however, will represent a very small fraction of the surface area and biofilms generated on the source materials. In addition, in many countries, plastics and other materials used in drinking-water systems are subject to standards, including tests to demonstrate that they do not support microbial growth (WHO, 2014).

There is currently no evidence to suggest a human health risk from microplastic-associated biofilms in drinking-water.

4.5 Conclusions and research needs

There is currently no evidence to suggest a human health risk from microplastic-associated biofilms in drinking-water.

While there are substantial gaps in knowledge, the potential risks from microplastic-associated microorganisms are far lower than the well-established risk posed by the high concentrations and diversity of pathogens present in human and livestock wastes in drinking-water sources. In addition, in terms of providing surfaces for attachment and transport of microorganisms including pathogens, the concentrations of microplastics reported in drinking-water sources are far lower than concentrations of non-plastic particles that contribute to normal turbidity in water.

The diversity of organisms in the plastisphere is constrained by environmental factors and material properties such as surface roughness and hydrophobicity (McCormick et al., 2016; Rummel et al., 2017; Oberbeckmann, Kreikemeyer, and Labrenz, 2018). These constraints are also likely to apply to pathogens. Drinking-water treatment is designed to remove particles and the use of both clarification processes and disinfection will further reduce the potential for any pathogens to reach drinking-water.

The potential risk from pathogens found on biofilms associated with microplastic is also far lower than on biofilms associated with water distribution systems. The surface area provided by the low concentrations of microplastics (see Chapter 2) that escape treatment is extremely small compared to the surface area of materials in distribution systems. Further, biofilms pose a low risk compared to other risks, including enteric pathogens, particularly in well managed drinking-water distribution systems. However, certain pathogens present in biofilms in distribution systems, such as *Legionella* spp., could result in a health burden (Cassini et al., 2018) to susceptible populations exposed to water in building-specific water systems such as hospitals, where water systems' materials and temperatures could encourage the growth of the pathogen within the distribution system. Regardless of source, routine disinfection of distribution systems can control the growth of biofilms and minimize exposure to opportunistic and obligate pathogens.

Research needs

To better understand microplastic-associated biofilms and their significance, the following research could be carried out:

- Further studies could be conducted on the factors that influence the composition and potential specificity of microplastic-associated biofilms.
- Studies could also consider the factors influencing biofilm formation on plastic surfaces, including microplastics, and how these factors vary for different plastic materials, and what organisms more commonly bind to plastic surfaces in freshwater systems.
- Research could be carried out to better understand the capacity of microplastics to transport pathogenic bacteria longer distances downstream, the rate of degradation in freshwater systems and the relative abundance and transport capacity of microplastics compared with other particles.
- Research could consider the risk of horizontal transfer of antimicrobial resistance genes in plastisphere microorganisms compared to other biofilms, such as those found in WWTPs.

5. Treatment technologies for removing microplastics from water

5.1 Introduction

Most drinking-water—whether from a tap, well, or bottle—comes from surface water or groundwater. Virtually all drinking-water supplies sourced from surface water are filtered and some receive further treatment. Groundwater is typically of higher quality as it is naturally filtered through soil and rocks when it passes into underground aquifers, and hence, it often receives less treatment, if any.

Since microplastics have been found in fresh water, primarily surface waters, understanding the effectiveness of drinking-water treatment in removing microplastics is important in assessing exposure of humans through drinking-water. Understanding the effectiveness of wastewater treatment is also important in the context of drinking-water since wastewater effluent is a key source of microplastics in surface waters (see section 2.2). This chapter therefore reviews the effectiveness of wastewater and drinking-water treatment processes for removal of microplastics.

Even though limited empirical data exist on the ability of different treatment systems to remove microplastics (see Box 5.1), considerable data do exist on the removal of particles similar to microplastics. One of the key roles of both drinking-water and wastewater treatment is to remove or reduce particles, and treatment processes are therefore expected to be effective in removing microplastics from water (Mason et al., 2016; Murphy et al., 2016; Mintenig et al., 2017; Trussell and Tate, 1979). Microplastics have characteristics similar to many natural particles. Depending on the type of treatment under consideration, properties relevant to removal can include size, density and surface charge (Tobiason et al., 2011). The mechanisms for removing

Box 5.1 Data limitations

As discussed in Chapter 2, accurate and standardized methods for determining microplastic concentrations and compositions in water and wastewater remain a significant challenge, with the majority of occurrence studies conducted in drinking-water and wastewater considered not fully reliable. Further, studies often use different detection methods. This means that some caution is required when interpreting and comparing the results of studies on the removal of microplastics in treatment and the occurrence data in fresh water and drinking-water. However, no study has been discounted at this stage given the paucity of data. Where quality scores are available, these have been included.

particles includes adsorption, enmeshment in coagulation floc aggregates, flotation, sedimentation, filtration and straining by size exclusion. Particles can also be removed using membrane processes such as microfiltration, ultrafiltration, nanofiltration and reverse osmosis.

5.2 Wastewater treatment

WWTPs are a principal barrier to the direct discharge of waterborne microplastic pollution into the aquatic environment. However, only a limited number of studies have examined microplastic removal through the various treatment processes (Sun et al., 2019). A review of 18 studies on the occurrence of microplastics in wastewater found that typical WWTP effluent has a lower median concentration of microplastic particles compared to the influent, although the range in effluent concentrations varied significantly (Koelmans et al., 2019). This may be an indication that some WWTP facilities have ineffective treatment practices or are not designed for optimal removal of microplastics (Magnusson and Norén, 2014). In these cases, discharges from WWTPs can represent routes for microplastics to enter into fresh waters and then possibly into drinking-water (Kay et al., 2018).

In many countries, significant efforts have been made to increase the quality of WWTP effluent to meet higher quality targets for surface water. Where such receiving waters are used as a drinking-water source, the microplastic load originating from the WWTP is expected to be significantly reduced. However, in low- and middle-income countries, only 33% of the population have sewer connections. Wastewater for the remaining 67% of the population is collected and treated in onsite systems or discharged directly to soil and water bodies. In addition, approximately 20% of household wastewater collected in sewers does not undergo at least secondary treatment (UNICEF/WHO, 2019). In these cases, the contribution of microplastics into the receiving water body is expected to be higher.

5.2.1 Studies assessing the efficacy of microplastic removal

According to available data, conventional wastewater treatment using primary and secondary treatment processes can effectively remove most microplastics from wastewater. Removals of more than 90% have been reported, with most of the microplastics removed during pre-treatment and primary treatment stages (Talvitie et al., 2017a). A large Italian WWTP (400 million L/day) reportedly removed 84% of microplastics >63 µm (Magni et al., 2019). However, the concentration of microplastics found in the influent wastewater was quite low, with an average of 2.5 particles/L in the

influent and 0.4 particles/L in the effluent following screening, grit and grease removal, biological treatment, sedimentation, sand filtration and disinfection. Data from a Scottish WWTP recorded average microplastic concentrations of 15.7 particles/L (size 598 ± 0.89 µm) in wastewater influent. Treatment removed 98.4% of microplastic particles, with much of the removal taking place in the grease removal process (Murphy et al., 2016). In Turkey, assessments of two WWTPs recorded between 12–36 particles/L in the influent and 2–9 particles/L in the secondary effluent, with overall removal of between 54–92% for plastic particles classified from <100 µm to 5000 µm (Gündoğdu et al., 2018). In a Finnish WWTP, pre-treatment and primary treatment removed 97% of microplastic particles, with activated sludge removing a further 7–20% for particles captured on sieves between 20–400 µm (Talvitie et al., 2017a).

Some final stage wastewater treatment technologies have also been very effective in enhancing microplastic removal from effluents. For example, between 95–99.9% of microplastics (>20 µm) were removed by particle removal technologies such as rapid sand filters, membrane bioreactors and dissolved air flotation (Talvitie et al., 2017b; Lares et al., 2018). Another study concluded that secondary and tertiary treatment processes were highly efficient in removing microplastics, with greater than 99.9% removal when samples were processed using a range of sieves with mesh sizes between 20–400 µm (Carr, Liu and Tesoro, 2016). Tertiary filtration of wastewater from a German WWTP completely removed microplastics >500 µm, and removed 93% of microplastics smaller than 500 µm (LoD 20 µm) and 97.7% of plastic classified as synthetic fibres (Mintenig et al., 2017). In another example of a highly treated wastewater, 0.28 particles/L (>25 µm) were identified after tertiary ultrafiltration and 0.21 particles/L (>25 µm) after reverse osmosis (Ziajahromi et al., 2017) (TAS = 12). These concentrations were below the concentrations found in theoretically particle-free blanks from the study by Uhl, Eftekhardadkhah, and Svendsen (2018). Wastewater treated using biologically aerated filters as a tertiary treatment saw no microplastic removal across the treatment (Talvitie et al., 2017a). A summary of these studies is included in Table 5.1.

Wastewater treatment can typically remove more than 90% of microplastic particles, with the highest removals seen after tertiary treatment such as filtration.

5.2.2 Factors influencing microplastic removal

The primary mechanisms for removing microplastics during wastewater treatment is through agglomeration into biological flocs followed by separation using sedimentation, flotation and filtration (Murphy et al., 2016; Talvitie et al., 2017a). During these solid-liquid separation processes, microplastics are concentrated and transferred from the

Table 5.1 Summary of microplastic removal reported from wastewater treatment studies

Author	System	Removal	Remarks	Quality score (TAS)[a]
Ziajahromi et al. (2017)	Secondary, tertiary and reverse osmosis treatment	90%	Removal considered relative to microplastics in primary treated effluent	12
Talvitie et al. (2017b)	Tertiary treatment: rapid sand filtration, membrane bioreactors and air flotation	95–99.9%	The smallest microplastics (20–100 µm) and fibres were the most common type of particle observed in influent and effluent	10
Murphy et al. (2016)	Removal across whole plants (consisting of pre-, primary and secondary treatment)	98.4%	Mean of 15.7 microplastic particles/L in influent (Size: 598 ± 89 µm); most removed with fat and grease removal	9
Lares et al. (2018)	Primary and secondary treatment	98.3%	Considered removal of microplastics >20 µm	9
Talvitie et al. (2017a)	Pre-, primary, secondary and tertiary treatment	Pre- and primary: 97% Secondary: 7–20% Tertiary: no removal	Most removal observed across pre and primary treatment processes	6
Carr, Liu and Tesoro (2016)	Secondary and tertiary treatment	99.9%	Tertiary treatment was biologically-aerated filter	6
Magni et al. (2019)	Removal across whole plant (consisting of pre-, primary, secondary and tertiary treatment)	84%	Solids skimming and settlement processes important for removal	—
Gündoğdu et al. (2018)	Removal across two whole plants (consisting of pre-, primary and secondary treatment)	54–92%	Low concentration of microplastics in the influent: 2.0 ± 0.3 particles/L	—
Mintenig et al., 2017	Pre- and post-tertiary filtration	93–97.7%	Most plastic particles in influent and effluent composed of polyester	—

[a] TAS = total accumulated score, as reported in Koelmans et al. (2019). The maximum score is 18 and is calculated by adding scores for nine quality criteria, where for each criterion, a score of 0, 1 or 2 is assigned. See the annex for an overview of the nine quality criteria and for each study, the individual scores against each criteria. TAS values are underlined when all underlying scores are non-zero.

water phase into the solid phase. Due to the hydrophobic nature of microplastics, many are expected to be removed with fats, oils and greases in grease traps, sewerage systems and floating debris. Observations of microplastic removal in grease traps at a municipal WWTP were consistent with this assumption: a significant proportion of microplastics were accumulated in the grease waste (19.67 microplastic particles/2.5 g), including microbeads (Murphy et al., 2016). Also, other studies have shown that filtration and other tertiary treatment stages can significantly reduce the total microplastic discharge. This removal is influenced by the surface characteristics of the microplastic (such as roughness, hydrophobicity and surface charge) as well as the size of the particles being filtered.

5.3 Drinking-water treatment

Drinking-water treatment plays an important role in reducing concentrations of microplastics that have been introduced into source waters. Ideally, all drinking-water that comes from surface water sources will undergo treatment prior to distribution. Typically, surface water is treated more substantively than groundwater, as groundwater is generally of higher quality due to natural filtration that occurs as it percolates through soil and rock before reaching underground aquifers.

Limited empirical data exist on the presence of microplastics in drinking-water and their removal across drinking-water treatment processes (Lancet Planetary Health, 2017). Only a few studies report concentrations of microplastics along the whole drinking-water treatment process (Pivokonsky et al., 2018; Uhl, Eftekhardadkhah, and Svendsen 2018; Mintenig et al., 2019). As such, no firm conclusions can be drawn. However, drinking-water treatment has proven effective in removing far more particles of smaller size and at far higher concentrations than those of microplastics. This fact combined with well-understood removal mechanisms point to rational conclusions on the removal of most microplastic particles in water treatment processes.

Drinking-water treatment has proven effective in removing far more particles of smaller size and at far higher concentrations than those of microplastics. This fact combined with well-understood removal mechanisms point to rational conclusions on the removal of microplastic particles in water treatment processes.

5.3.1 Studies assessing microplastic removal efficacy

As noted earlier, empirical evidence for the removal of microplastics across different drinking-water treatment systems is currently limited to a few studies.

Mintenig et al. (2019) (TAS = 15) monitored microplastics at different stages of the drinking-water treatment and distribution system from a groundwater source. Low numbers of microplastic particles were detected in both the raw water and the treated drinking-water at concentrations between 0 to 0.007 particles/L, with an overall mean of 0.0007 particles/L. There were no significant differences between concentrations and types of microplastics in the source water and treated water. Microplastics identified were PE, PA, PEST, PVC and epoxy resin and were between 50 and 150 µm in size. The authors suggested that the abrasion of plastic equipment used during water treatment or distribution was a likely source of the plastic particles detected in the water samples. Pivokonsky et al. (2018) (TAS = 11) reported microplastic removal efficiency of between 70–82% across three water treatment processes that used conventional coagulation, clarification and filtration processes. However, inter-stage monitoring was not carried out in this study.

In an assessment of 24 water treatment plants in Norway that applied coagulation and filtration processes, very low concentrations of microplastics were found in treated water (Uhl, Efteckhardadkhah, and Svendsen, 2018) (TAS = 9). The authors demonstrated that the concentrations of microplastic particles in treated water were lower than those in the raw water, confirming that coagulation and filtration were effective in microplastic removal. Some contrasting results have been seen in laboratory studies that investigated the application of iron and aluminum coagulants for the removal of PE microplastics (Ma et al., 2019). Up to 40% removal of PE was observed when using aluminum coagulants, higher than that observed using iron coagulants. Removal was enhanced as the plastic particles became smaller. The presence of a coagulant aid (polyacrylamide) had a positive and substantial effect on removal.

5.3.2 Factors influencing microplastic removal

Drinking-water treatment processes can effectively eliminate particles and colloids across a wide size range (from dissolved/colloidal materials to particles of a few mm). For example, an optimized treatment process is capable of removing pathogenic bacteria and *Cryptosporidium* (US EPA, 2003, 2006), which are typically <5 µm. Larger particles are more easily removed. Although a wide range of microplastic types have been identified, for the purpose of water treatment, the physicochemical properties of the material will determine the mechanisms of removal. Particle removal processes used in drinking-water treatment can typically be divided into: (1) clarification processes that use combinations of coagulation, flocculation, sedimentation/flotation and filtration; and (2) membrane processes.

Clarification processes

Clarification processes such as those involving coagulation are the most common methods of removing particles in drinking-water treatment. During coagulation, small particles and colloids are destabilized with the addition of a coagulant chemical, allowing formation of aggregates known as microflocs. Microflocs are typically encouraged to grow into larger flocs during slow mixing in a process known as flocculation. Large aggregates can then be settled or float in the water (Letterman and Yiacoumi, 2011). Generally, for coagulation and flocculation, particle properties can impact their agglomeration and entrapment in flocs, including surface charge, size, distribution and shape profile, concentration and the strength of bonds formed between particles when captured in a floc (Letterman and Yiacoumi, 2011). Most of the residual particles that remain are then removed by granular media filtration processes. Typically, sand grains with a diameter around 500 µm are used as the granular media, although media down to 200 µm can be used (Crittenden et al., 2012). Particles between 80–100 µm cannot pass through the spaces between the filter media and are strained from the water. Particles smaller than a micrometre can be removed when they attract to the media grains in the filter. The attachment mechanisms depend on the size, shape and charge of the particles being filtered, as well as the hydraulic conditions present in the filter. Very low concentrations of residual suspended solids should be present in water that has been treated by a well-operated granular media filtration system (Tobiason et al., 2011).

When separating solids from liquid, water quality and operating conditions can limit the effectiveness of the process. As most plastic particles are hydrophobic, adsorption of organic compounds can occur (Napper et al., 2015). Because of this interaction, plastics are likely to adopt the characteristics of background organic matter, which will influence their removal profile in different solid-liquid separation processes. Humic acids, which can form a large proportion of organic matter, for example, can stabilize particles in water and prevent aggregation (Jarvis et al., 2005). However, since microplastics are relatively large compared to other particles removed in drinking-water treatment, the effect may not be as important as it is for other particles. The presence of organic matter might be more relevant for nanoplastics. Understanding which micro- and nanoplastics behave like other environmental particles is critical for appropriate risk characterization in drinking-water treatment. Hydraulic conditions can also influence the effective removal of particulates, including microplastics, during clarification processes. For example, flocs can be broken by shear forces or changes of pH, forming smaller particles that may be more difficult to remove during clarification (Jarvis et al., 2005; Slavik et al., 2012).

Membrane processes

Membrane processes can be divided into diffusional membranes (reverse osmosis and the lower end of nanofiltration) and porous membranes (microfiltration, ultrafiltration and

the upper end of nanofiltration). For diffusional membranes, only dissolved substances can diffuse through the membrane; no particles should pass through the membrane. For porous membranes, the nominal pore size determines the size of particles that can pass through the membrane. Particles above the pore size will be rejected. Typically microfiltration rejects particles >1 µm, ultrafiltration rejects particles >0.01 µm, and nanofiltration >0.001 µm. For all membranes, these cut-offs are far below the size of microplastics that have been detected in drinking-water to date. Consequently, no microplastics above these size ranges should pass through membranes unless the membranes are damaged (which is usually monitored by routine integrity testing). This conclusion is consistent with the limited data available for removal of microplastics from drinking-water using membranes. In a laboratory study, PE microplastics were completely rejected by ultrafiltration membranes (Ma et al., 2019).

5.3.3 Other considerations

To date, no information is available to indicate if and how microplastics are transformed during oxidative processes used in water treatment, such as ozonation, chlorination or advanced oxidation. There is no reason to assume that these processes will not interact and react with microplastics present in the water. However, whether the processes affect the surface of microplastics or cause further breakdown of the particle into smaller particles is poorly understood.

An interesting side note in the consideration of drinking-water and wastewater treatment processes is whether they contribute microplastics into water themselves. For example, many membranes are composed of polymeric materials. Similarly, processes such as ion-exchange used for water softening, de-ionization and removal of nitrate and natural organic matter often use polymeric plastic materials (e.g. PS and polyacrylics). These processes are exposed to abrasion and wear over time which might release low quantities of microplastics into water. In a similar vein, high shear-rate processes used in both drinking-water and wastewater treatment (e.g. in mixing systems) may degrade plastic particles into smaller pieces, in turn making them more challenging to remove. Water pipes composed of plastic materials will also be subject to abrasive processes. Further research is needed to determine how these processes influence microplastic levels in water, if they do at all.

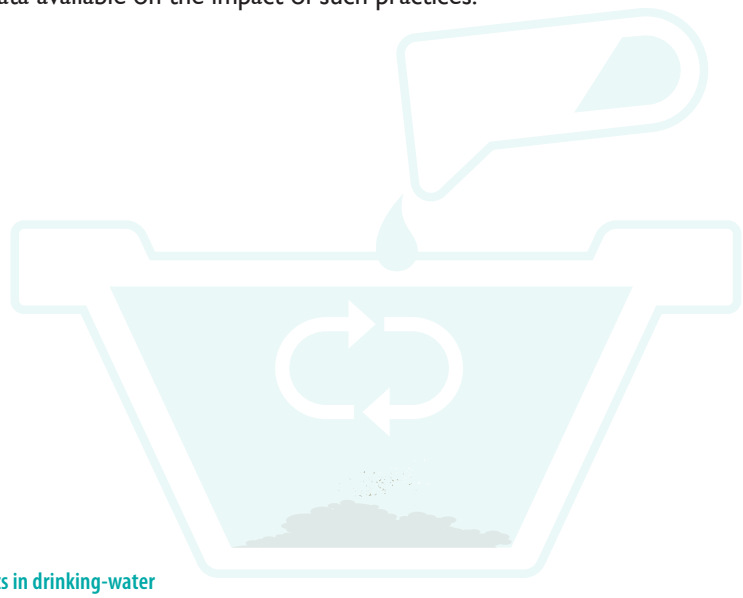
5.3.4 Turbidity as an indicator of microplastic removal

Given the low concentrations of microplastics in drinking-water sources, it is difficult to monitor the efficacy of microplastic removal across water treatment processes such as filtration. The standard approach for monitoring efficacy of filtration is to monitor turbidity in treated water (WHO, 2017b). Turbidity describes the cloudiness of water

caused by suspended particles of mineral, chemical or biological origin. Microplastics may contribute to the turbidity of water if present in sufficient concentrations. The advantages of turbidity measurements are simplicity, relatively low cost and speed of results. However, different turbidity-causing materials can exhibit different relationships between particle concentration and the resultant turbidity signal (Farrell et al., 2018). It is likely that different types of microplastics will also exhibit unique relationships between particle concentration and turbidity. Microplastics may also be associated with other types of particles, for example, when they become incorporated into flocs. This makes it challenging to assess removal of specific types of particle, such as microplastics, using a bulk water parameter such as turbidity. For these reasons, turbidity should be used as a general indicator of water quality and for general operational monitoring and process efficacy including particle removal, but should not be used to directly infer microplastic concentrations. The same considerations should be given to other particle monitoring instruments such as particle counters, which have become a common tool for process and water quality monitoring.

5.4 Considerations for drinking-water and wastewater treatment sludge

An important consideration for both wastewater and drinking-water treatment is that the plastics are usually not destroyed, but rather transferred from one phase to another. Sludge disposal methods must therefore be considered since sludge application to land is a probable route for re-contamination of the environment. Equally, where membrane cleaning or back-flushing of filters is practiced, waste streams may be returned directly to the aquatic environment. Although it is clear that use and/or disposal practices for waste products containing microplastics warrants special consideration, there are limited data available on the impact of such practices.



5.5 Conclusions and research needs

Limited data on wastewater treatment confirm it is effective in removing microplastics along with other particles. Wastewater treatment can typically remove more than 90% of microplastic particles, with the highest removals seen after tertiary treatment such as filtration.

Only limited quantified data are available to demonstrate the efficacy of microplastic removal across drinking-water treatment processes. However, conventional drinking-water treatment (coagulation, sedimentation and filtration) is designed to remove particulates and is therefore expected to effectively remove microplastics, particularly when optimized to produce treated water of low turbidity. When optimized, conventional treatment can remove particles smaller than a micrometre. Advanced treatment using membranes would be expected to achieve 100% removal of microplastics larger than 0.001 to 1 μm, with removal capabilities >0.001 μm for nanofiltration, >0.01 μm for ultrafiltration and >1 μm for microfiltration.

An important consideration is that wastewater and drinking-water treatment is not available nor optimized in many countries. In these settings, there may be higher levels of microplastics in drinking-water and freshwater sources. However, the health risks associated with exposure to pathogens and other chemicals present in untreated or inadequately treated water will be far greater. By addressing the bigger problem of exposure to untreated or inadequately treated water, communities can simultaneously address the smaller concern related to microplastics in surface water and other drinking-water supplies.

Since microplastics removed through both wastewater and drinking-water treatment will be incorporated into sludge or other waste streams, there is potential for particles to return to the environment depending on the use or disposal practices.

Research needs

Although water treatment can be effective in removing particles, there is limited data specific to microplastics. To support human health risk assessment and management options, the following data gaps related to water treatment need to be addressed:

- More research is needed to understand the fate of microplastics across different wastewater and drinking-water treatment processes (such as clarification processes and oxidation) under different operational circumstances, including optimal and sub-optimal operation and the influence of particle size, shape and chemical composition on removal efficacy.
- There is a need to better understand particle composition pre- and post-water treatment, including in distribution systems. The role of microplastic breakdown and abrasion in water treatment systems, as well as the microplastic contribution from the processes themselves should be considered.
- More knowledge is needed to understand the presence and removal of nanoplastic particles in water and wastewater treatment processes once standard methods for nanoplastics are available.
- There is a need to better understand the relationships between turbidity (and particle counts) and microplastic concentrations throughout the treatment processes.
- Research is needed to understand the significance of the potential return of microplastics to the environment from sludge and other treatment waste streams.

6. Managing plastic and microplastic pollution in the environment

6.1 Benefits of managing plastic and microplastic pollution

Irrespective of any risks to human health from ingestion of microplastics in drinking-water, improved management of plastics and a reduction in plastic pollution holds multiple benefits for the environment and human well-being.

A growing body of evidence confirms that larger plastic waste and macroplastic debris—themselves precursors to microplastic pollution—can harm wildlife and the environment. Researchers have estimated that as of 2015, only 9% of plastic ever produced has been recycled, and that, without action by 2050, there will be 12 billion tonnes of plastic in landfills and the environment (Geyer, Jambeck, and Law, 2017). Presently, plastic litter can be found throughout the environment including on streets, fields and beaches, disturbing quality of life, and in some cases impacting tourism-related livelihoods. Poorly managed plastic waste streams can contribute to the obstruction of storm drains and sewers, which prevents proper drainage and increases sanitation-related risks. Incineration of plastic waste, with its resulting air pollution, and the climate change-inducing greenhouse gas associated with plastic production, could impact human health and the environment.

Irrespective of any risks to human health from ingestion of microplastics in drinking-water, improved management of plastics and a reduction in plastic pollution holds multiple benefits for the environment and human well-being.

Concerns relate also to microplastics. If plastic emissions into the environment continue at current rates, there may be widespread risks associated with microplastics to aquatic ecosystems within a century (SAPEA, 2019), with potentially concurrent increases in human exposure.

6.2 Responses to growing concern over plastic pollution

In response to concerns about the impact of plastic and microplastic pollution, public awareness and engagement has increased. Activities have ranged from schools adopting educational activities on plastics, to civil society launching campaigns and some industries pledging to reduce plastic use. Political commitment is also growing.

Ministers of Environment from 157 countries committed to significantly reduce single-use plastic products by 2030 at the 4th UN Environment Assembly in March 2019 (UNEP, 2019a). This followed an agreement at the previous Assembly to recognize the importance of long-term elimination of microplastics from the oceans. In May 2019, governments agreed to amend the Basel Convention to require the consent of importing countries for mixed and contaminated plastic waste (UNEP, 1989, 2019b). The aim is to improve regulation of the global trade in plastic waste to support better and safer management.

More than 60 countries are already taxing or banning single-use plastics, primarily plastic bags (UNEP, 2018). Countries such as the UK and the USA have developed legislation to eliminate plastic microbeads in personal care products such as scrubs and toothpastes (US Government, 2015; UK Government, 2017) while the European Union is currently considering such legislation (ECHA, 2019).

6.3 Options to curb plastic and microplastic pollution

As outlined in Chapter 2, microplastics can come from a number of sources including from the degradation of larger plastic items found in the environment, frequently as a consequence of the poor management of used and discarded plastic items. With only limited data on the number and composition of microplastic particles in drinking-water, it is not possible to identify the most important sources of microplastics in drinking-water, making it difficult to determine what actions might best be directed in the short- to medium-term. However, it is likely that microplastics in fresh water contribute to the presence of microplastics in drinking-water where there is an inadequate filtration barrier.

Strategies to better manage plastics and reduce the use of plastics where feasible, are critical to the effort to minimize adverse impacts of discarded plastic. Strategies to minimize microplastic inputs can confer other benefits as well. For example, installing and optimizing wastewater treatment will not only reduce the direct input of microplastics to the aquatic environment but will also reduce the input of enteric pathogenic microorganisms and a number of chemical micropollutants into drinking-water sources. Similarly, optimizing the performance of processes that remove microplastics from water sources will also reduce concentrations of microbial and chemical hazards in drinking-water.

Where possible, preventing new sources of plastics from entering the environment and/or reducing existing sources would be appropriate. Care must be taken, however, when considering mitigation strategies for existing plastics so that solving one problem

does not simply create a new one. This is particularly important in view of the limited data on sources of different sizes and types of microplastics, including the very small particles that are currently not well quantified. The removal of particles in wastewater and drinking-water treatment that are then returned to the environment in backwash, sludge biosolids or other waste streams, either through direct discharge or from run-off from receiving land, is an area requiring study before appropriate decisions can be made as to what actions might be required.

Where simple, low cost actions can be taken to make even a small difference to plastic inputs to the environment, it would be sensible to implement them. This is in line with the Rio declaration and the Rio statement of the precautionary principle, which considers cost–effectiveness: "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (United Nations, 1992).

The benefits of plastic must also be considered before introducing policies and initiatives. For example, single-use syringes play an important role in preventing infections. Priority management actions should be "no regrets", in that they confer multiple benefits and/or that they are cost-effective.

A few broadly categorized preventive measures to reduce the entry of plastics into the environment are described below. These are outlined in the EU Plastics Strategy (European Commission, 2018), adopted in January 2018, which contains measures in four broad groups:

1. Improve the economics and quality of plastic recycling
2. Curb plastic waste and littering
3. Drive innovation and investment towards circular solutions and sustainable manufacturing practices to decrease waste inputs to the environment
4. Engage in international efforts to minimize and eliminate plastic waste

Other measures proposed to address plastic pollution include bans, fees (e.g. charges or taxes on disposable bags and bottles), Extended Producer Responsibility, voluntary agreements and mandatory consideration of non-plastic alternatives, with a recommendation to focus actions on plastic waste streams with high volumes, high-emission profiles and high-hazard plastic uses (SAPEA, 2019). With respect to single-use plastics, the United Nations Environment Programme (UNEP, 2018) has proposed a 10-step roadmap for policymakers to curb waste. The report also recognizes the importance of broader cooperation, from raising awareness among consumers to public-private partnerships.

7. Conclusions, recommendations and knowledge gaps

7.1 Conclusions

Microplastics are ubiquitous in the environment, including in the water cycle. They have been detected in marine water, wastewater, fresh water and both tap and bottled water. However, the quality and quantity of data vary across different water types and the data on occurrence in drinking-water are limited.

In drinking-water, the typical characteristics of microplastics (i.e. composition including polymer type, size and shape) and their route into bottled water and tap water is still uncertain, although the frequency of detected polymers is generally consistent with production volumes and plastic density. Important sources of microplastics into fresh water are surface run-off and wastewater effluent, but there are insufficient data to quantify these inputs and determine more specific primary sources. Further, some contamination may also occur during treatment, distribution or bottling processes.

Study results should be interpreted in the context of the methods used, for example, smaller mesh sizes are generally used in drinking-water studies compared to freshwater studies, contributing to higher particle counts. In general, there is a need to improve, standardize and harmonize microplastic sampling and analysis in water; most studies conducted to date are not considered fully reliable. Box 2.2 summarizes areas that likely require the most improvement.

There are no studies on the impacts of ingested microplastics on human health and there are only a limited number of animal studies of questionable reliability and relevance. Some data suggest a very limited uptake and impact of microplastics <50 µm in laboratory animals at high concentrations, but the relevance to humans is unknown. These studies require confirmation under realistic exposure conditions before firm conclusions can be drawn. Despite limited health data, several inferences could be made with respect to human health risks:

- Although it is not possible to draw any firm conclusion on toxicity related to the physical hazard of plastic **particles**, particularly the nano size particles through drinking-water exposure, no reliable information suggests it is a concern. Humans have ingested microplastics and other particles in the environment for decades with no related indication of adverse health effects. In addition, drinking-water treatment is effective at removing particles. Although there is only limited quantified evidence on microplastic removal across water treatment processes, conventional

drinking-water treatment (coagulation, sedimentation and filtration) is expected to effectively remove microplastics since conventional treatment is designed to remove particulates, particularly when optimized to produce treated water of low turbidity. Advanced treatment, particularly membrane filtration, would be expected to achieve 100% removal of particles >0.001 µm for nanofiltration, >0.01 µm for ultrafiltration and >1 µm for microfiltration.

- The substantial margin between a theoretical conservative exposure to a range of chemical contaminants detected in microplastics through drinking-water and the level at which no or limited adverse effects were seen, indicates there is a low health concern for **chemicals** associated with microplastics. A summary of the estimated MOEs and implications for human health are included in Table 3.3. Applying assumptions with higher particle numbers in smaller size ranges does not change the conclusions.
- The risks from pathogens in microplastic-associated **biofilms** is considered far lower than the well-established risk posed by the high concentrations and diversity of pathogens present in human and livestock waste, which often make their way into drinking-water sources with inadequate treatment. Further, the relative surface area for attachment and transport of microorganisms, including pathogens, is far lower for microplastics based on the concentrations reported in drinking-water and drinking-water sources compared to the concentrations of non-plastic particles that contribute to normal turbidity in water. For microplastics that are not removed during drinking-water treatment, these particles also provide an extremely small surface area for the development of biofilms compared to drinking-water distribution systems and therefore, the relative significance of microplastics-associated biofilms is still likely to be negligible. Regardless of source, drinking-water treatment is largely designed to remove particles and the use of both clarification processes and disinfection, including disinfection in distribution systems, will reduce the potential for any pathogens to be present in drinking-water.

Future research and emerging science to address data gaps will enable more accurate and reliable assessments of exposure and potential impacts to human health.

A summary of the potential hazards and estimated risk is included in Table 7.1.

Table 7.1 Summary of key hazards associated with microplastics in drinking-water and estimated health risk

Potential hazard	Data available	Preliminary risk assessment
Particle (physical hazard)	No human studies are available on ingested microplastics. Effects have primarily been observed in a limited number of animal studies at high concentrations that are not applicable to drinking-water. Relevance of these studies to humans is unknown. Limited information is available on the uptake of microplastics, particularly for particles <150 µm.	Insufficient information to draw firm conclusions, although no reliable information suggests health concerns.
Monomers (chemical hazards, e.g. 1,3-butadiene, ethylene oxide, vinyl chloride)	Six of the eight most hazardous monomers have WHO drinking-water guideline values. Residual monomer content in microplastics is unknown.	
Additives (chemical hazards, e.g. BPA, DEHP, lead)	Relevant additives are subject to risk assessments, with established toxicological point of departures. For lead, the provisional WHO guideline value is based on practical achievability. No safe limit for lead has been established. Some data are available on concentrations of additives detected in microplastics.	A MOE assessment was conducted for chemicals that have been detected in microplastics, are of toxicological concern and have adequate or accepted PODs for deriving a MOE. The MOE assessment indicates a low health concern since there are several orders of magnitude difference between the estimated exposure (based on a very conservative exposure scenario for microplastic-contaminated drinking-water) and the level at which no or limited adverse effects are known to occur.
Sorbed chemicals (chemical hazards, e.g. cadmium, DDT, PAHs, PCBs)	Relevant contaminants are subject to risk assessments, with established toxicological point of departures. Some data are available on concentrations of sorbed pollutants detected in microplastics.	
Biofilms (microbial hazards)	There are only a limited number of occurrence studies in fresh water.	Low health concern considering the relative concentration of microplastics compared to other particles that pathogens can adhere to in fresh water and the well-established risk posed by the high concentrations and diversity of pathogens present in human and livestock waste in drinking-water sources.

Considerations for exposure and risk
Absorption of smaller microplastics may be higher compared to larger microplastics based on limited studies examining exposure at high concentrations. Elevated exposure, however, is likely to overwhelm biological particle clearance mechanisms. Smaller particles may be more susceptible to adsorb biologically-significant proteins and molecules. The influence of shape and surface chemistry impacting toxicity is unknown for ingested microplastics. Conventional drinking-water treatment is effective at removing particles and is capable of removing particles smaller than a micrometre when optimized to produce treated water of low turbidity. Advanced treatment can remove smaller particles (e.g. nanofiltration can remove particles > 0.001 µm).
Weathering and biodegradation may degrade polymers into monomers but the extent to which this occurs is unknown. However, unbound monomers are likely to leach into the environment, resulting in extremely small concentrations in drinking-water sources. Many monomers are likely to convert to more stable compounds in water (e.g. propylene oxide would convert to propylene glycol, which has low toxicity). Materials in contact with drinking-water, including plastics, should be approved for such use to ensure they do not leach substances, including monomers, at concentrations of concern.
Smaller additives with low molecular weight can migrate faster than larger additives. Migration may potentially increase as plastics age and weather. However, relative to other emission routes of additives to the environment, leaching from microplastic will likely be small. Inconclusive and limited evidence is available on the relative importance of microplastics acting as a vector of transport of chemical additives. Efforts have been taken to reduce the use of additives-of-concern from plastics. Materials in contact with drinking-water, including plastics, should be approved for such use to ensure they do not leach substances, including additives, at concentrations of concern.
The hydrophobic nature of microplastics implies that they can have the potential to accumulate POPs. Sediment, algae, the lipid fraction of biological organisms and microplastics all have similar capacities to accumulate POPs. Given the larger mass of soil, algae and aquatic organisms, the relative importance of microplastics to act as a vector of transport of POPs is likely negligible in comparison to other exposure routes.
Based on limited studies, microplastics may enable pathogens to travel longer distances in freshwater environments. Based on limited studies, biofilms on microplastics may contribute to antimicrobial resistance. Drinking-water treatment (clarification and membrane processes) is effective at removing particles, including microorganisms attached to particles. For microplastics that are not removed during treatment, the relative significance of microplastic-associated biofilms is still likely negligible due to the larger mass of drinking-water distribution systems and their subsequent ability to support more biofilms, compared to microplastics. Disinfection, including in distribution systems, can inactivate pathogens and control their growth.

An important consideration is that wastewater and drinking-water treatment is not available nor optimized in many places. In these settings, there may be higher levels of microplastics in drinking-water and freshwater sources. However, the health risks associated with exposure to pathogens present in untreated or inadequately treated water will be far greater. By addressing the bigger problem of exposure to untreated or inadequately treated water, communities can simultaneously address the smaller concern related to microplastics in surface water and other drinking-water supplies.

7.2 Recommendations

Routine monitoring of microplastics in drinking-water is not recommended at this time, as there is no evidence to indicate a human health concern. Concerns over microplastics in drinking-water should not divert resources of water suppliers and regulators from other important issues, including the removal of microbial pathogens, which remains the most significant risk to human health from drinking-water. Water suppliers should establish water safety plans and ensure that control measures, including water treatment processes, are optimized for particle removal, and microbial safety, which will incidentally improve the removal of microplastic particles.

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However, more research is needed to better understand the occurrence of microplastics in the environment and in media that may result in human exposure. Although routine monitoring is not recommended, it would be appropriate to undertake targeted, well-designed and quality-controlled investigative studies to better understand the sources and occurrence of microplastics in fresh water and drinking-water, the efficacy of different treatment processes and combinations of processes, and the significance of the potential return of microplastics to the environment from treatment waste streams including the application of sludge biosolids to agricultural land.

To help inform water supply management options, more information is needed on the source of microplastic pollution in fresh water and drinking-water, as well as the mechanisms and efficacy of removing plastic particles in both wastewater and drinking-water treatment. However, regardless of the human health risk posed by exposure to microplastics in drinking-water, improving management of plastics and reducing the use of plastics where feasible, to minimize the number of plastics released into the environment is recommended because these actions can confer other benefits to

the environment and human well-being. Strategies to minimize microplastic inputs can result in other benefits as well, for example, improvements to water treatment can result in the removal of a range of contaminants, from microbial pathogens to emerging contaminants including microplastics in both wastewater and drinking-water, providing a more sustainable and comprehensive solution than microplastic removal alone.

7.3 Knowledge gaps and research needs

There are a number of data gaps that preclude a more accurate and reliable assessment of exposure and potential impacts to human health. This section summarizes the highest priority research needs to better assess human health risks and inform management actions.

- **Development of standard methods:** There is a need to improve microplastic sampling and analysis using quality-assured methods. Standard methods for measuring microplastic particles, including nanoplastics in water should be developed to improve the quality of studies and enable researchers to compare and reproduce results. To date, there are no data on the occurrence of nanoplastics in drinking-water or drinking-water sources.
- **More studies on the occurrence and characteristics of microplastics:** There is a need to better understand the occurrence of microplastics in the environment and in drinking-water using quality-assured methods to determine numbers, shapes, sizes, composition and sources of microplastics.
- **Improved understanding of sources of microplastics into fresh water:** Although surface run-off and wastewater effluent are considered the main sources of microplastics into fresh water, better data are required to quantify their contributions relative to other inputs and identify the original sources of contamination through these pathways. This may require establishing reliable methods to track origins and identify major sources of microplastics in fresh water.
- **More data on the occurrence and fate of microplastics throughout the water supply chain:** In drinking-water, an understanding of the occurrence and fate of microplastics is needed throughout the water supply chain, pre- and post-treatment and in sub-optimal conditions to determine the proportion of and types of microplastic particles coming from the freshwater environment, abstraction, treatment systems, distribution systems and bottling and to better characterize effectiveness of water treatment.
- **More data on the return and significance of treatment waste streams:** Since plastics are usually not destroyed, but rather transferred from one phase to

another, a better understanding on the return and significance of microplastics to the environment from drinking-water and wastewater treatment waste streams, including sludge, is needed. There are currently limited data available on this.

- **Increased understanding of toxicological effects of microplastics following ingestion:** Toxicological testing of microplastics has been limited mostly to aquatic organisms, and there are no toxicological or epidemiological studies that would inform human health risk assessment for microplastic ingestion. Some toxicological endpoints in a limited number of studies have been conducted but there are questions regarding the reliability of these studies, which are generally limited to assessing effects under high exposure scenarios with unclear relevance to human exposure via drinking-water at significantly lower concentrations. Quality-assured toxicological data are needed from cell models and/or animals on the most common forms of plastic particles appropriate for human health risk assessment. A better understanding is also needed on the characteristics of microplastics that are most predictive of their toxicity.
- **More data on the uptake and fate of microplastics in the GI tract:** The current database of information on plastic particle absorption and toxicity is limited to a few studies using PE, PET or PS. A better understanding is needed on the uptake of microplastic particles, the fate of microplastics in the GI tract and the influence of particle size, shape and chemical composition, particularly in relation to nanoplastics.
- **Better understanding of overall microplastic exposures in the environment:** The significance of exposure to microplastics in drinking-water also needs to consider relative exposure from other sources such as food and air. It is difficult with available information to make a robust quantitative estimate on the relative contribution from different sources. A better understanding of occurrence in these environmental compartments, including quality of these studies, will be useful in articulating relative exposure through drinking-water compared to other sources.

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Annex 1: Systematic review and other studies of microplastics in fresh water and drinking-water

This section summarizes a systematic review commissioned by WHO titled, *Microplastics in freshwaters and drinking-water: Critical review and assessment of data quality* (Koelmans et al., 2019). It also includes a summary of the studies on microplastics in drinking-water.

A.1 Overview of systematic review

As part of the systematic review, Koelmans et al. proposed several best practices for sampling, extracting and detecting microplastics and divided these best practices into nine quality criteria. The authors then assessed available studies on the occurrence of microplastics in drinking-water, surface water, groundwater and wastewater against these nine quality criteria to determine the overall reliability of the studies. They also summarized data on microplastic concentrations, polymer types and particle shapes. A summary of the data on concentrations, polymer types and particle shapes is included in sections 2.5–2.7.

A.2 Systematic review methods

A.2.1 Literature search approach

The authors reviewed 50 studies reporting microplastic concentrations in drinking-water, freshwater sources and wastewater. Because some studies reported data on microplastics in more than one water type, 56 records were reviewed (2 tap water, 3 bottled water, 2 water exiting a DWTP, 1 groundwater, 30 surface water, and 18 wastewater). Most papers were retrieved from the Scopus database using the search strings '*microplastic AND (bottle OR surface OR tap OR wastewater OR groundwater)*'. Three studies were identified from the grey literature (i.e. not peer-reviewed) via Google searches, using the same or similar key-word combinations as used for the Scopus database. The systematic search was performed until August 2018. Only those studies that reported original concentration data were reviewed.

A.2.2 Study characteristics

For each study the following characteristics were summarized in tabular form (see Table S1 in Koelmans et al., 2019):

- Reference, country (area)
- Source (water type)
- Treatment (for wastewater and drinking-water treatment)
- Sampling date; size and shape (of microplastics detected)
- Polymer types (of microplastics detected)
- Chemicals (analysed in water or polymer)
- Value (of microplastics detected in water sample)
- Quality assurance applied (detection limit, blanks)
- Sampling method
- Analysis method
- Comments

A.2.3 Quantitative quality assessment

The reliability of data in these studies was assessed against nine "crucial" criteria, which are detailed below. These criteria are an adaptation of the methods developed for microplastic biota samples by Hermsen et al. (2018), which has been recognized in the recent report from The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) (2019).

For each criterion a value of 2 (reliable), 1 (reliable to limited extent) or 0 (unreliable) was assigned. A TAS was calculated by adding scores for individual criteria for a maximum of 18 points (See Table A.1 below). Assuming all individual criterion are genuinely crucial, an overall quality score can be defined by multiplying the individual scores, followed by a ^{2}Log X transformation to obtain a linear scale for a maximum score of nine. Such an approach implies that if even one of the crucial criteria is not met, the overall quality score will be zero and the data reported in the study are not considered fully reliable.

Quality criteria

1. **Sampling methods.** This criterion assessed whether sampling was described in sufficient detail, including, for instance, date, location, and materials used. Specific sub-criteria were defined for wastewater, groundwater, surface water, tap water and bottled water.

2. **Sample size.** To render a sample representative of the type of water studied, a minimum sample size was defined, or for bottled water, a minimum number of bottles to be analysed. The sample size needs to be sufficiently large to reliably detect at least one microplastic particle with statistical rigor.
3. **Sample processing and storage.** When transferring a primary sample (e.g. material in a net) to a sampling bottle or preserving or storing samples before reaching the laboratory, certain criteria need to be met, such as confirmation that fixatives do not affect the particles. To minimize contamination, plastic materials should not be used to sample or store samples.
4. **Laboratory preparation.** Prior to analysing a sample, certain measures need to be taken in the laboratory, including wearing cotton laboratory coats, and pre-rinsing and cleaning materials to minimize airborne contamination.
5. **Clean air conditions.** Clean air conditions are also needed to minimize contamination with airborne microplastic particles or fibres. Samples should be handled in a laminar-flow cabinet or clean-air laboratory.
6. **Negative controls.** To confirm and correct for contamination or to demonstrate absence of contamination, replicated procedural blanks should be analysed. Blanks should be reported with particle counts, including standard deviations, and actual sample results should be corrected for the blank values and indicated as such.
7. **Positive controls.** To confirm a sufficiently high recovery of particles during filtration, digestion transfer and analysis, representative and replicated positive controls should be performed.
8. **Sample treatment.** To ensure the quality of visual inspection and subsequent sample analysis, a sample digestion step should be performed for surface water and wastewater samples. Tap water and bottled water do not require a digestion step and thus were automatically assigned 2 points.
9. **Polymer identification.** To ensure reliable assessment of plastic particles, the identity of the polymer needs to be confirmed by using FTIR or Raman spectroscopy, pyrolysis-GC/MS or thermogravimetric analyser-GC/MS techniques. Where subsampling is required, best practices for subsampling and subsequent polymer identification will depend on the microplastic size classes and technologies applied.

A detailed description of scoring criteria is provided in Koelmans et al., 2019.

A.3 Overview of systematic review results

Studies differed widely in sampling and analytical methods. Few studies reported a detection limit. Generally, surface water samples employed plankton nets or trawls to collect high-volume samples. Other sampling methods (also used on other water types), included pump and spot sampling. As for analytical methods, most studies sorted the samples through sieving or density-separation and treated the samples chemically to remove organic material that otherwise may interfere with the microplastic identification process. Chemical treatments differed widely but hydrogen peroxide, which has been demonstrated to have minimal impacts on the microplastic weights, count and shapes within an exposure of 48 hours, was often used. Several studies, however, treated the samples at higher temperatures, which may impact the polymer. Polymer identification mostly used FTIR methodologies.

Quality assurance remained limited, often lacking positive controls, sufficient blank controls or measures to reduce airborne contamination of samples. The average scores per criterion across 52 studies were lower than 1 for the criteria *sample treatment* (0.93), *polymer identification* (0.89), *laboratory preparation* (0.77), *clean air conditions* (0.64), and *positive controls* (0.21). Key areas to improve sampling and analytical methods are included in Box 2.2.

Average TAS were 13.7 for bottled water, 12.5 for water exiting a DWTP, 11.5 for tap water, 7.9 for surface water and 7.3 for wastewater studies. This ranking likely reflects the relative ease of analysing the different water types, although there were only three studies assessed for bottled water, two for tap water and two for water exiting a DWTP. The overall quality scores were zero, except for four studies: Wang et al. (2018, surface water) received a quality score of 6; Mason et al. (2018, bottled water) scored a 5; Ziajahromi et al. (2017, wastewater) scored 3; and Hendrickson, Minor and Schreiner (2018, wastewater) scored a 2. This means that 46 studies were considered not fully reliable on at least one crucial criteria. However, improvements in quality assurance in assessment and analysis methods may be occurring already, since the four studies that received positive scores in all criteria were published more recently, in 2017 and 2018. See Table A.1 for an overview of individual and total scores from studies reporting microplastics in drinking-water, fresh water and wastewater.

The fact that data or a study may not be fully reliable according to these criteria does not imply that the data are not useful. For instance, data may provide insights collectively on the extent of contamination in the environment and the most important polymer types and shapes, even if the sampling method is not described in a reproducible way. A study may provide data with some systematic error due to sample contamination, which may still be useful for comparisons within that study.

Table A.1 Overview of individual and accumulated scores from studies reporting microplastic concentrations in drinking-water, fresh water and wastewater

Author	Water type	Sampling methods	Sample size	Sample processing and storage	Laboratory preparation
Mason et al. (2018)	Bottle	1	2	2	1
Schymanski et al. (2018)	Bottle	1	1	2	2
Oβmann et al. (2018)	Bottle	1	1	2	2
Mintenig et al., 2019	Tap	2	2	2	2
Strand et al., (2018)	Tap	2	0	2	1
Uhl et al. (2018)	Tap	1	0	1	2
Kosuth et al. (2018)	Tap	0	0	0	2
Mintenig et al. 2019	DWTP	2	1	2	2
Pivokonsky et al. (2018)	DWTP	1	1	2	1
Mintenig et al. (2019)	Ground	2	1	2	2
Wang et al. (2018)	Surface	2	1	1	2
Hendrickson et al. (2018)	Surface	2	1	2	1
Di and Wang (2018)	Surface	2	0	2	2
Mani et al. (2015)	Surface	2	2	1	1
Wang et al. (2017)	Surface	1	0	1	2
Baldwin et al. (2016)	Surface	2	1	1	1
Cable et al. (2017)	Surface	2	1	1	1
Dris et al. (2018a)	Surface	2	2	0	1
Lares et al. (2018)	Surface	1	0	1	2
Rodrigues et al. (2018)	Surface	2	2	1	1
Su et al. (2016)	Surface	2	1	1	1
Zhang et al. (2017)	Surface	2	1	1	1
Dris et al. (2015)	Surface	2	1	2	1
Estahbanati and Fahrenfeld (2016)	Surface	2	2	1	0
Hoellein et al. (2017)	Surface	2	1	2	0
Mason et al. (2016b)	Surface	2	1	1	0
Sighicelli et al. (2018)	Surface	2	2	1	0
Vermaire et al. (2017)	Surface	2	1	2	0
Xiong et al. (2018)	Surface	2	1	0	1
Anderson et al. (2017)	Surface	2	1	1	0
Faure et al. (2015)	Surface	1	2	1	1

	Clean air conditions	Negative controls	Positive controls	Sample treatment	Polymer ID	Quality score (TAS)[a]	Author
	2	2	1	2	1	**14**	Mason et al. (2018)
	2	2	0	2	2	**14**	Schymanski et al. (2018)
	2	2	0	2	1	**13**	Oβmann et al. (2018)
	1	2	0	2	2	**15**	Mintenig et al., 2019
	1	2	2	2	2	**14**	Strand et al., (2018)
	1	2	0	2	0	**9**	Uhl et al. (2018)
	2	2	0	2	0	**8**	Kosuth et al. (2018)
	1	2	0	2	2	**14**	Mintenig et al. 2019
	1	2	0	1	2	**11**	Pivokonsky et al. (2018)
	1	2	0	2	2	**14**	Mintenig et al. (2019)
	2	2	2	2	1	**15**	Wang et al. (2018)
	1	1	1	1	1	**11**	Hendrickson et al. (2018)
	0	0	1	2	1	**10**	Di and Wang (2018)
	1	1	0	1	1	**10**	Mani et al. (2015)
	1	2	0	2	1	**10**	Wang et al. (2017)
	1	2	0	1	0	**9**	Baldwin et al. (2016)
	1	1	0	1	1	**9**	Cable et al. (2017)
	1	1	0	1	1	**9**	Dris et al. (2018a)
	1	2	0	1	1	**9**	Lares et al. (2018)
	0	1	0	1	1	**9**	Rodrigues et al. (2018)
	1	1	0	1	1	**9**	Su et al. (2016)
	2	0	0	0	2	**9**	Zhang et al. (2017)
	1	1	0	0	0	**8**	Dris et al. (2015)
	0	1	1	1	0	**8**	Estahbanati and Fahrenfeld (2016)
	0	1	0	1	1	**8**	Hoellein et al. (2017)
	0	2	0	1	1	**8**	Mason et al. (2016b)
	0	0	0	2	1	**8**	Sighicelli et al. (2018)
	0	2	0	1	0	**8**	Vermaire et al. (2017)
	1	1	0	1	1	**8**	Xiong et al. (2018)
	0	1	0	1	1	**7**	Anderson et al. (2017)
	0	0	0	1	1	**7**	Faure et al. (2015)

Table A.1 Overview of individual and accumulated scores from studies reporting microplastic concentrations in drinking-water, fresh water and wastewater (continued)

Author	Water type	Sampling methods	Sample size	Sample processing and storage	Laboratory preparation
McCormick et al. (2016)	Surface	1	1	1	0
Miller et al. (2017)	Surface	1	0	1	1
McCormick et al. (2014)	Surface	1	1	1	0
Fischer et al. (2016)	Surface	2	1	1	0
Free et al. (2014)	Surface	2	1	1	0
Lahens et al. (2018)	Surface	1	1	1	0
Leslie et al. (2017)	Surface	1	0	2	0
Eriksen et al. (2013)	Surface	2	1	1	0
Zhang et al. (2015)	Surface	2	1	0	0
Mintenig et al. (2017)	WWTP	2	2	2	1
Ziajahromi et al. (2017)	WWTP	2	2	1	1
Simon et al. (2018)	WWTP	1	1	0	1
Lares et al. (2018)	WWTP	2	0	1	2
Talvitie et al. (2017a)	WWTP	2	1	1	1
Murphy et al. (2016)	WWTP	1	1	2	2
Mason et al. (2016a)	WWTP	2	2	1	0
Vollertsen and Hansen (2017)	WWTP	0	2	1	0
Carr et al. (2016)	WWTP	2	2	1	0
Magnusson and Norén (2014)	WWTP	2	2	1	0
Michielssen et al. (2016)	WWTP	2	1	2	0
Talvitie et al. (2017b)	WWTP	2	0	1	0
Vermaire et al. (2017)	WWTP	1	0	2	0
Dyachenko et al. (2017)	WWTP	1	0	1	0
Leslie et al. (2017)	WWTP	1	0	2	0
Dris et al. (2015)	WWTP	1	0	0	1
Talvitie et al. (2015)	WWTP	2	1	0	0
Browne et al. (2011)	WWTP	0	0	1	0

[a] TAS = total accumulated score. The maximum score is 18 and is calculated by adding scores for nine quality criteria; for each criterion, a score of 0, 1 or 2 is assigned. TAS values are underlined when all underlying scores are non-zero.

Source: Koelmans et al. (2019) with the addition of quality scores for Strand et al. (2018) and Uhl et al. (2018).

Clean air conditions	Negative controls	Positive controls	Sample treatment	Polymer ID	Quality score (TAS)[a]	Author
0	2	0	1	1	**7**	McCormick et al. (2016)
1	2	0	0	1	**7**	Miller et al. (2017)
0	2	0	1	0	**6**	McCormick et al. (2014)
0	0	0	1	0	**5**	Fischer et al. (2016)
0	0	0	1	0	**5**	Free et al. (2014)
0	0	0	1	1	**5**	Lahens et al. (2018)
1	1	0	0	0	**5**	Leslie et al. (2017)
0	0	0	0	0	**4**	Eriksen et al. (2013)
0	0	0	0	1	**4**	Zhang et al. (2015)
1	2	0	1	2	**13**	Mintenig et al. (2017)
1	1	1	1	2	**12**	Ziajahromi et al. (2017)
1	2	2	2	1	**11**	Simon et al. (2018)
1	2	0	1	1	**10**	Lares et al. (2018)
1	2	0	0	2	**10**	Talvitie et al. (2017a)
1	1	0	0	1	**9**	Murphy et al. (2016)
0	2	0	1	0	**8**	Mason et al. (2016a)
0	0	2	1	1	**7**	Vollertsen and Hansen (2017)
0	0	0	0	1	**6**	Carr et al. (2016)
0	0	0	0	1	**6**	Magnusson and Norén (2014)
0	1	0	0	0	**6**	Michielssen et al. (2016)
0	2	0	0	1	**6**	Talvitie et al. (2017b)
0	2	0	1	0	**6**	Vermaire et al. (2017)
0	0	1	1	1	**5**	Dyachenko et al. (2017)
1	1	0	0	0	**5**	Leslie et al. (2017)
1	1	0	0	0	**4**	Dris et al. (2015)
0	1	0	0	0	**4**	Talvitie et al. (2015)
0	0	0	0	2	**3**	Browne et al. (2011)

A.4 Summary of drinking-water studies

Since there are a limited number of drinking-water studies, with even less considered reliable, each of the drinking-water studies is described in more detail below. They are described in order of decreasing study quality, as determined by the TAS quantitative assessment, primarily from Koelmans et al. (2019). One additional unscored study identified from the grey literature had insufficient detail to assess fully the study quality but a short description is included in this section for completeness.

1. Mintenig et al. (2019) analysed groundwater and drinking-water derived from the groundwater for the presence of microplastics. Samples were taken at different locations within the drinking-water supply chain. Large volume samples were filtered through a 3 µm mesh filter and particles over 20 µm were characterised using FTIR imaging. Four 150 L volume blank samples were found to contain both fibres and particles (0.67 particles/L, 0.3 fibres/L). Fibre numbers in blank samples exceed those in raw and treated waters indicating the fibres were not present in the water but were introduced during sample processing. Particles in blanks were mainly blue PP and SAN and were attributed to contamination from the filter unit and were excluded from the analysis. Concentrations reported ranged from 0 to 0.007 particles/L in both raw water and drinking-water with an overall mean of 0.0007 particles/L. These particles were identified as PE, PA, PEST, PVC or epoxy resin and were between 50 and 150 µm in size. The authors suggested the abrasion of plastic equipment used during water treatment or transport was a likely source of the plastic particles detected in the water samples.

2. Mason, Welch and Neratko (2018) tested 259 individual bottles from 27 different lots across 11 brands of bottled water purchased from 19 locations in 9 countries. Samples were stained with Nile Red (a fluorescent dye used to stain particles) and filtered through 1.5 µm pore filter. Large particles >100 µm were removed and about half were analysed by FTIR. The remaining smaller fluorescing particles were counted using a software system. Blank samples were subject to the same procedures and were found to contain on average 4.15 particles/L (>100 µm) and 23.5 particles/L (between 6.5–100 µm). Nearly all (93%) of the bottles showed some evidence of microplastic contamination. After correcting for blanks, the average count of particles >100 µm was 10.4 particles/L of bottled water, ranging from 0 to 66 particles/L . Fragments were the most common shape (66%) followed by fibres (13%) and films (12%). PP, the most common plastic used for bottle caps, was the most common polymer (54%) and 4% of particles showed presence of industrial lubricants. The authors suggested that the contamination was at least partially coming from the packaging and/or the bottling process itself. Smaller particles in

the range 6.5–100 µm were identified by Nile Red tagging without spectroscopic confirmation, and the average count reported was 315 particles/L of bottled water (range of 0 to over 10 000 particles/L). All the tagged larger particles analysed by FTIR showed some evidence of polymeric content, increasing the authors' confidence in the tagging method in this study. Based on this and other studies that had detected small microplastics in bottled water, the authors expected that the smaller particles were plastic or of some other anthropogenic origin, although no confirmatory spectroscopic analysis was conducted.

3. Strand et al. (2018) examined drinking-water from 17 sites around Denmark. All drinking-water in Denmark is derived from groundwater with the exception of one small island not included in the study (Andreas Herfelt, Danish Ministry of Environment and Food, personal communication, November 2018). A 50 L sample from each site was filtered through a 10 µm stainless-steel filter. The filters were examined by microscopy for microplastic-like particles with sizes >100 µm. The predominant type of microplastic-like particles observed were fibres (82%). On average 0.312 particles/L and a maximum of 0.6 particles/L >100 µm were observed. Five blank 50 L samples were analysed and found to contain on average 13.2 microplastic-like particles (0.26 particles/L). Results were used to generate a limit of detection of 0.58 particles/L. In 16 of the 17 drinking-water samples, the numbers were below the limit of detection. Of the total particles identified, 124 (44%) microplastic-like particles were further characterised by FTIR. Of the microplastic-like particles, 3% were verified as microplastic, whereas the majority consisted of cellulose-like material (76%), with the remainder having poor spectra (10%), unknown (7%) or protein-like material (4%). The types of microplastic particles detected in the tap water samples were PET, PP and PS. Some further analysis of particles in the range of 10 to 100 µm also found low levels of microplastic.

4. Schymanski et al. (2018) used micro-Raman spectroscopy to identify microplastics in bottled water where particle sizes are in the low micrometre range. The authors tested the microplastic content of water from 22 different returnable and single-use plastic bottles, 3 beverage cartons and 9 glass bottles purchased in Germany. Samples were filtered through a 3 µm pore size filter. Larger (50–500 µm) and very small (1–50 µm) microplastic fragments were found in every type of water sample. Most (80%) of the microplastic particles found were between 5 and 20 µm in size. The average microplastic content reported was 118 ± 88 particles/L (range 28–241 particles/L) in returnable bottles, 14 ± 14 particles/L (range 2–44 particles/L) in single-use plastic bottles, 11 ± 8 particles/L (range 5–20 particles/L) in beverage cartons and surprisingly 50 ± 52 particles/L (range 4–156 particles/L) in glass bottles. Only the returnable bottles showed a statistically significant difference from the blank

value (14 ± 13 particles/L). Most of the particles in water from returnable plastic bottles were identified as PET (84%) and PP (7%) consistent with the material used to manufacture bottles (PET) and the caps (PP). In other bottle types microplastic particles other than PET were found, for example PE or other polyolefins. The authors noted that beverage cartons are coated with polyethylene foils and caps are treated with lubricants and that the findings indicate that the packaging itself may release microparticles.

5. Oßmann et al. (2018) analysed 32 samples of bottled mineral water purchased in Germany for concentrations of microplastics particles. Using 0.4 µm membrane filters and micro-Raman spectroscopy on five 1 mm^2 areas of the filter, particles as small as 1 µm were analysed. Microplastics were found in water samples from all bottle types. The average count of microplastics reported in mineral water was 2649 particles/L in single-use PET bottles, 4889 particles/L in reusable PET bottle and between 3074 particles/L (excluding an outlier) and 6292 particles/L (all samples) in glass bottles. On average 384 microplastic particles/L (range 0–1175) were found in blank samples, consisting mainly of PP, some of PS, PE and PET. Whilst in plastic bottles, the predominant polymer type was PET, in glass bottles various polymers such as PE or styrene-butadiene-copolymer were found. The authors concluded that in addition to the packaging itself, other contamination sources have to be considered. Over 95% of the detected microplastics particles found in plastic bottles were smaller than 5 µm and over 75% of those found in glass bottles were smaller than 5 µm.

6. Pivokonsky et al. (2018) investigated microplastic concentrations in fresh water and drinking-water. Researchers studied three DWTPs in the Czech Republic and analysed raw and treated water for microplastics. All waters were derived from surface sources. Analysis involved peroxide oxidation, sequential filtering through 5 and 0.2 µm filters; sections of the filters were analysed by electron microscopy to quantify particle numbers, shapes and sizes. Numbers were corrected based on the finding of the spectroscopic analysis. Particle characterisation was by FTIR on particles above 10 µm and Raman spectroscopy on particles above 1 µm. Microplastics were found in all water samples in the range 1473 to 3605 particles/L in raw water and 338 to 628 particles/L in treated drinking-water. Background contamination, determined by analysing blank filters, was less than 5% of the abundance of microplastics detected and was considered negligible. Typical removal across drinking-water treatment was reported as 70–80%. Microplastics smaller than 10 µm were the most plentiful in both raw and treated water samples, accounting for up to 95% of the particles found. Fragments clearly prevailed at two of the DWTPs in both the raw and treated waters and fibres together with fragments predominated at the remaining DWTP. Despite 12 different materials forming the microplastics identified, the majority of the microplastics (70%) were comprised of PET, PP and PE.

7. Uhl, Eftekhardadkhah, and Svendsen (2018) studied raw water, treated water and drinking-water from the distribution system at 24 water works in Norway. Of those, 20 used surface water and 4 used groundwater. All samples were taken as triplicates of 1 L volume, sampling was done by professional personnel, and special attention was given to avoid contamination during sampling and analysis. Samples were filtered through commercial glass fibre filter papers. Analysis was done microscopically and in addition to the 216 bottles, 72 blanks were analysed. In the blanks, 0.5 microplastic particles/L were found on average, showing some contamination from processing samples in the laboratory. A statistical analysis of the results from the triplicates yielded a LoD of 0.9 microplastic particles/L and a LoQ of 4.1 microplastic particles/L, both with a 67% confidence level. No differences between groundwater and surface water were found. At 20 of 24 sites, the concentration in raw water was below the LoQ. Four of the raw-water sites showed average concentrations of up to 2.7 particles/L. Concentrations in treated water were, lower than in raw water, with a 67% confidence level. Except for 1 of the 72 triplicates, all averages were below the LoQ (67%). Only one triplicate of drinking-water taken from the distribution system showed an average concentration above the LoD, i.e. 5.5 microplastic particles/L. However, that could be attributed to environmental contamination due to rough sampling conditions. The study also presented some evidence for contamination of water samples from air when blank bottles were exposed open to air for 24 hours.

8. Kosuth, Mason and Wattenberg (2018) investigated the presence of anthropogenic particles in 159 samples of globally sourced tap water. Samples were collected in 500 ml PE bottles, vacuum filtered through a cellulose filter with a pore size of 2.5 µm and analysed using staining of natural organic matter with Rose Bengal, (a fluorescent dye,) and microscopy. Since no confirmatory spectroscopic analyses, such as FTIR, were conducted, the unstained particles were described as anthropogenic particles rather than microplastics. Of the tap water samples analysed, 81% were found to contain anthropogenic particles. The majority of these particles were fibres (98.3%) between 0.1–5 mm in length, with an average of 0.96 mm. The range reported was 0 to 61 particles/L, with an overall mean of 5.45 particles/L. Of the 30 total deionized blanks, 5 were reported with one anthropogenic particle in them and the others were reported with none. For the three brands of bottled water also included in the study, the average reported concentration of anthropogenic particles was 3.57 particles/L. Of the 539 particles found, the most common colour was blue, followed by red/pink, and brown. Water sourced from more developed nations had an average particle count higher than that sourced from less developed nations.

9. Results from an unpublished study (Mahon et al., 2017) reported maximum concentrations of microplastics of 6.5 particles/L in untreated private well-water

samples and 1.6 particles/L in a public water supply in Ireland. The report contained insufficient details on the methods of analysis to interpret or contextualize these results. The public water supply came from a lake and the treatment process involved fine screening (5 mm), coagulation, settlement, pH correction, rapid-gravity filtration, UV treatment, disinfection and fluoridation. The authors considered the ability of fibres to pass through such a robust treatment system raises the question of whether systems that employ fewer treatment stages may not be as efficient in capturing microplastics, but without further details of contamination control measures, the results should be treated with caution.

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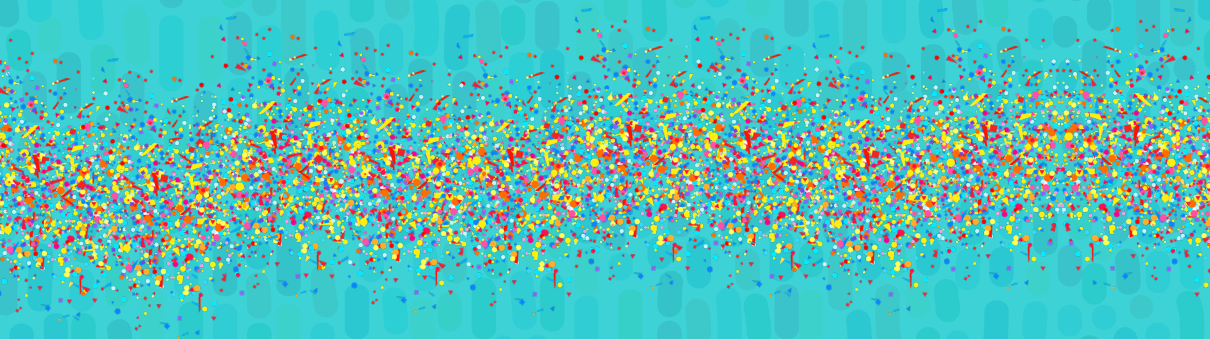

For more information contact:

Water, Sanitation, Hygiene and Health
World Health Organization
20 Avenue Appia
1211 Geneva 27
Switzerland

gdwq@who.int

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