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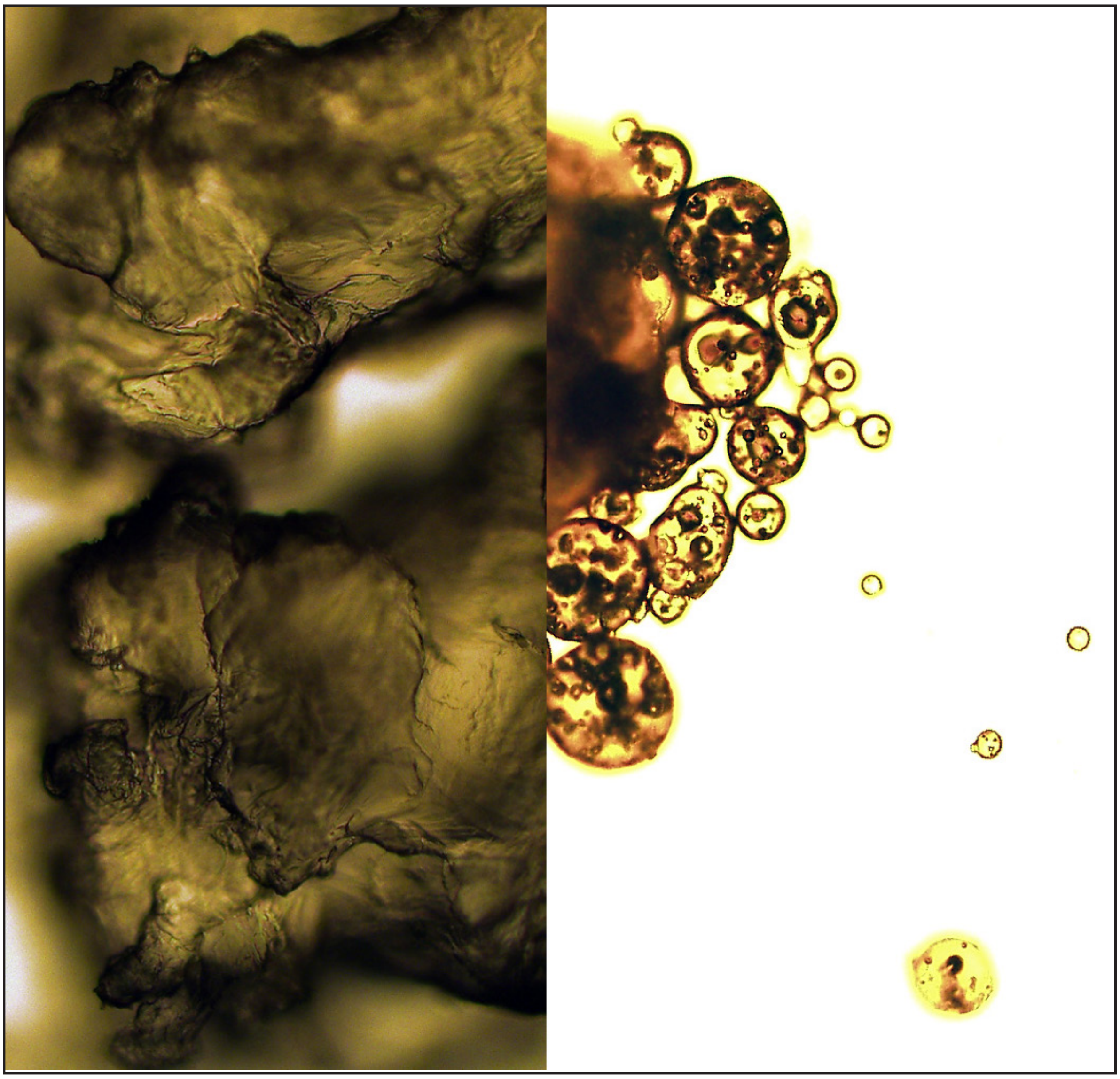
Microplastics in marine environments: Occurrence, distribution and effects



Norwegian Institute for Water Research
– an institute in the Environmental Research Alliance of Norway

REPORT

Main Office
Gaustadalléen 21
NO-0349 Oslo, Norway
Phone (47) 22 18 51 00
Telefax (47) 22 18 52 00
Internet: www.niva.no

NIVA Region South
Jon Lilletuns vei 3
NO-4879 Grimstad, Norway
Phone (47) 22 18 51 00
Telefax (47) 37 04 45 13

NIVA Region East
Sandvikaveien 59
NO-2312 Ottestad, Norway
Phone (47) 22 18 51 00
Telefax (47) 62 57 66 53

NIVA Region West
Thormøhlens gate 53 D
NO-5006 Bergen Norway
Phone (47) 22 18 51 00
Telefax (47) 55 31 22 14

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Abstract

This report reviews the current understanding of the occurrence, distribution and effects of microplastics on the marine environment.

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Kristoffer Næs

Kevin Thomas
Project Manager

Kristoffer Næs
Research Director

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Microplastics in marine environments: Occurrence, distribution and effects

Preface

Most members of the public are aware of, or have seen the impacts of, litter pollution on the marine environment, so common are scenes of beaches covered in litter. The extent of this pollution is such that the amount of marine litter found along the Norwegian coast and the coast of Svalbard has been described as unacceptable. Much of this litter is in the form of plastic, with global use and production steadily increasing since mass production started in the 1940s, annual global production is now close to 300 million tonnes. What we don't see is plastic in the form of very small particles, so-called 'microplastics' that pollutes much of the marine environment. This report reviews the current understanding of the occurrence, distribution and effects of microplastics on the marine environment.

Oslo, December 2014

Kevin V Thomas

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Summary

The use and production of plastic has dramatically increased over the past 65 years. Plastic is used in many everyday products that improve the quality of life globally, yet around 50% of the plastic produced is used in disposable products that generate a substantial amount of waste. Plastic litter, arising from the inappropriate disposal of plastic products is a major global problem. Most plastics are chemically inert material that is not easily broken down in the marine environment resulting in plastic littering our oceans. The presence of litter in the marine environment has a direct impact on marine species that can ingest or become entangled in such litter.

Over the past decade there has been a realisation that plastic in the form of very small particles (<5 mm), so-called 'microplastic', pollutes much of the marine environment. These microplastics occur due to the release of manufactured (primary) microplastics in various products and the breakdown of larger plastic litter (secondary microplastics). Primary microplastics are found in personal care products, such as exfoliators and toothpastes, air-blasting technologies for clearing surfaces like boats and machinery from rust and human medicine, serving as vectors for drug delivery. The plastics industry also uses pre-production microplastic resin pellets typically < 5 mm in diameter and these are also ubiquitous in the marine environment. Secondary microplastics arise from the abiotic breakdown of larger plastic pieces in the environment or shed from fibrous synthetic materials, for example during washing. Treated wastewater is a known source of such fibrous microplastics with up to 100 particles L^{-1} being released into the environment. It is also likely that fragmentation process continues down to the nano-scale, resulting in the formation of nanoplastic particles, however this has yet to be quantified.

Microplastics are ubiquitous in the world's oceans and they have been found in both the Atlantic and the Pacific oceans and their adjacent seas, in both coastal areas and offshore. The proportion of samples containing microplastics ranges widely, but most studies have found microplastics in the majority of the samples collected (i.e. > 60%). Buoyancy is a key parameter when considering the fate of microplastics. Positively and negatively buoyant particles will be found in the upper reaches of the water column, while those that are negatively buoyant will work their way down over time to the seabed and the sediment. Fouling can influence buoyancy by increasing the density of a particle and cause it to slowly sink. Concentrations of microplastics in the water column range from less than 1 particle m^{-3} to several hundred particles m^{-3}, but measurements are inconsistent in terms of both sampling methods (device, mesh size and depth layer(s)) and units measured, highlighting the need for scientific conventions and standardizations with respect to sampling and quantification of pelagic microplastics. Much of the debris found on sediment is plastic (up to 96%) with sediments and beaches being a sink for microplastics. As many as 120 particles L^{-1} sediment have been reported. Fibers are often the dominant type of microplastics found in the water column and sediments.

Organisms are known to ingest microplastic particles. Many commercially important marine organisms are known to contain microplastics with several possible routes for exposure; for example via the mouth and

thereby the digestive system or via the gills. Ingestion of microplastics is well known and the digestive system is often examined when looking for the presence of microplastic. Exposure via the gills has not been demonstrated in the environment, but several suspension-feeding organisms have been reported to contain microplastics and this might be due to uptake over the gills. The digestive system of a wild caught fish typically contains between 1 and 7 particles, although no studies have yet demonstrated the accumulation of microparticles in the fish gut.

Plastic debris pollutes oceanic habitats from pole to pole: they are found in the open ocean, on shorelines of even the most remote islands and in the deep sea. At global scale several studies identified large-scale convergence zones of plastic debris due to the major ocean currents. High concentrations of microplastics have been found at five oceanic gyres (North Atlantic, South Atlantic, South Indian, North Pacific and South Pacific), and in addition predicts a hitherto unreported patch in the Barents Sea. The great spatial heterogeneity of microplastics at large and mesoscale (10s of km) makes it difficult to extrapolate local monitoring data to larger areas. Long-term monitoring is required to monitor the load of microplastics in the marine environment, however such data are scarce. Beach surveys report an increase in microplastics, but with little data this is generally difficult to support. Attempts to balance the quantities of plastic discharged with those measured highlights a 100-fold difference between measured and predicted loads as well highlighting an important gap in the size distribution of floating plastic debris. It has been hypothesised that there is substantial loss of plastic from the ocean surface, most likely due to the fast breakdown of plastic fragments from mm to μm scale, the preferential submersion of small-sized plastic with high surface:volume ratio and reduced buoyancy due to biofouling, ingestion by marine organisms and subsequent defecation as well as yet unidentified processes.

Plastic also contains additives, chemicals added to improve the desirable properties of the plastic product. Many of these additives are known hazardous substances and can leach from the plastic surface. Plastics once released into the environment can also accumulate known persistent organic pollutants (POPs). Surveys of contaminant in plastic particles collected from beaches suggest that concentrations measured may be representative of the environment these particles were sampled from. Plastic particles have the potential to act as vectors for the transport and release of sorbed contaminants and additives. While transfer of contaminants from ingested plastic particles and debris into organisms has been demonstrated in laboratory exposures, it is at present uncertain whether contaminated plastic present in the environment can affect contaminant bioaccumulation into marine organisms.

It is clear that marine organisms ingest microplastics and that laboratory experiments show that this can result in harm. To our knowledge there are no documented reports of direct effects of microplastic ingestion on wild organisms. The effects of microplastics on marine organisms are typically sub-lethal, such as reduced feeding and increased uptake of certain contaminants (e.g. polychlorinatedbiphenyls). Laboratory exposure to microplastics shows negative impact such as a reduction in the growth of marine worms and changes in gene regulation in fish.

There is a lack of data on the levels of microplastics present in the Norwegian environment and there is an urgent need to evaluate the extent of microplastic pollution around the coast of Norway and Svalbard.

The levels of anthropogenic particles (10–500 µm) in the Skagerrak seem lower than those found in the Baltic, however these data are not conclusive. What is clear is that northern fulmars (*Fulmarus glacialis*) are consuming plastics. Recent findings suggest that 95% of northern fulmars in the North Sea had plastic in their stomachs and that 58% contained levels above the 0.1g identified as an OSPAR Commission environmental quality objective. With respect to the Norwegian coast and specifically the Skagerrak, 50% of investigated northern fulmars contained levels above 0.1g.

Sammendrag

Plastbruk og produksjon har økt dramatisk de siste 65 årene. Plastprodukter er med på å bedre livskvaliteten til mennesker over hele verden, men rundt 50 % av plastproduktene er engangsprodukter som dermed genererer en betydelig mengde avfall. Plastsøppel, som følge av uheldig håndtering av plastprodukter, er et stort globalt miljøproblem. De fleste plasttypene er kjemisk inert materiale som er tungt nedbrytbart i det marine miljø. Tilstedeværelsen av søppel i det marine miljøet har en direkte negativ innvirkning på marine arter; det kan føre til drukning av marine pattedyr som vikler seg inn i det og også inntak av plastsøppelet (misoppfatter det for føde).

I løpet av det siste tiåret har det vært en erkjennelse av at plast i form av svært små partikler (<5 mm), såkalte "mikroplast", forurenser mye av det marine miljø. Mikroplast entrer miljøet på to hovedmåter; utslipp av produserte (primær mikroplast) mikroplastpartikler og nedbryting av større plastbiter (sekundær microplast). Primære mikroplastpartikler er funnet i personligpleie produkter, for eksempel ansiktsrens og tannkrem, luftrenseteknikker for å ta vekk rust fra overflater på båter og maskiner og også innen humanmedisin hvor mikroplast fungerer som vektorer for levering av legemidler. Plastindustrien bruker også såkalt pre-produksjon pellets som vanligvis er <5 mm i diameter, og disse er vanlige å finne i det marine miljøet. Sekundære mikroplastpartikler oppstår som sagt fra abiotiske nedbryting av større plastbiter, men en annen kilde til sekundær mikroplast er fiber som slites av under klesvask av syntetiske materialer. Behandlet avløpsvann er en kjent kilde til slike fibrøse mikroplastpartikler med opp til 100 partikler L^{-1} som er beregnet sluppet ut i omgivelsene. Det er også sannsynlig at fragmenteringsprosessen av plastbiter fortsetter ned til nano-skala, noe som resulterer i dannelsen av «nanoplastpartikler», men dette er ennå ikke kvantifisert.

Mikroplast er vid spredt i verdenshavene; Atlanterhavet og Stillehavet og nærliggende havområder, både i kystnære områder og til havs. Andelen av prøver som inneholder mikroplast varierer sterkt, men de fleste studier har funnet mikroplast i størsteparten av prøvene (dvs.> 60 %). Oppdrift er en viktig parameter når man vurderer skjebnen til mikroplast i havet. Partikler med positiv oppdrift (lettere enn sjøvann) vil bli funnet i de øvre delene av vannsøylen, mens de som er negativ oppdrift vil med tid synke ned til havbunnen og sedimentene. Begroing av mikroorganismer kan påvirke oppdriften til plasten ved å øke tettheten av en partikkel, og få den til å synke langsomt. Konsentrasjoner av mikroplast i vannsøylen rangerer fra mindre enn 1 partikkel m^{-3} til flere hundre partikler m^{-3}, men målinger kan være vanskelig å sammenligne pga. forskjeller i prøvetakingsmetoder (enhet, maskevidde og dybde lag (e)) og enheter som måles. Dette fremhever behovet for vitenskapelige standardisering med hensyn til prøvetaking og kvantifisering av pelagisk mikroplast. Mye av søppelet som er på strender og i sedimentene er plast (inntil 96 %), og sedimenter og strender ser ut til å være et oppsamlingssted for mikroplast. Så mange som 120 partikler L^{-1} sediment har blitt rapportert. Fiber er ofte den dominerende typen mikroplast funnet i vannsøylen og i sedimentene.

Det er påvist at marine organismer inntar mikroplastpartikler og dette gjelder også kommersielt viktige marine organismer. Det er flere ulike mulige eksponeringsveier; for eksempel via munnen og dermed fordøyelsessystemet, eller via gjellene. Svelging av mikroplast er godt kjent og fordøyelsessystemet er ofte undersøkt når man leter etter tilstedeværelse av mikroplast. Eksponering via gjellene er ikke vist i miljøet, men flere filtrerende organismer har blitt rapportert å inneholde mikroplast og dette kan være på grunn av opptak over gjellene. Fordøyelsessystemet til villfisk inneholder typisk mellom 1 og 7 partikler, men ingen studier har så langt vist at mikroplastpartiklene akkumulerer i fiskens tarm.

Plastbiter forurenser oseaniske habitater fra pol til pol; de er funnet i det åpne havet, på strender til selv de mest avsidesliggende øyer og i dyphavet. På global skala har flere studier identifisert store områder bestående av høye konsentrasjoner av plastbiter på grunn av de store havstrømmene. Høye konsentrasjoner av mikroplast har blitt funnet i fem oseaniske «gyrene» (Nord-atlanteren, Sør-atlanteren, Sør-indiske hav, Nord-Stillehavet og Sør-Stillehavet). Det er i tillegg mistenkt et hittil urapportert område i Barentshavet. Den store variasjonen i tettheten av mikroplast i miljøet og mesoskala (10-talls km) gjør det vanskelig å ekstrapolere lokale overvåkingsdata til større områder. Langsiktig overvåking er nødvendig for å overvåke belastningen av mikroplast i det marine miljø, men slike data er mangelvare. Strandundersøkelser rapporterer en økning i mikroplast, men med lite data er dette er generelt vanskelig å underbygge. Forsøk på å regne ut mengden plast sluppet ut i havet og mengden rapportert fra miljøprøver ser det ut til å gi en 100-gangers forskjell mellom utregnet konsentrasjoner og faktiske konsentrasjoner. Det er også et viktig gap i størrelsesfordelingen (visse størrelser er underrepresentert) av flytende mikroplast man finner i havet. Det har vært diskutert om det betydelige tapet av plast fra havoverflaten mest sannsynlig er på grunn av rask nedbryting av plastfragmenter fra millimeter til mikrometer skala, økt synkeevne av plast med høyt forhold mellom overflate og volum og redusert oppdrift på grunn av begroing, inntak av marine organismer og påfølgende defekasjon, samt ennå uidentifiserte prosesser. Plast inneholder såkalte additiver; kjemikalier som tilsettes for å forbedre de ønskelige egenskaper av plastproduktet. Mange av disse tilsetningsstoffer er uønskede i naturen og kan lekke ut av plastoverflaten. I tillegg kan også plast oppkonsentrere allerede tilstedeværende kjent persistente organiske miljøgifter (POPs) i naturen og kan fungere som vektorer for transport og eksponering.

Det er observert at marine organismer får i seg mikroplast, og laboratorieforsøk viser at dette kan resultere i negative effekter. Så vidt vi vet er det ingen dokumenterte rapporter om direkte effekter av mikroplast inntak på ville organismer. Effektene av mikroplast på marine organismer er typisk sub-letale, som redusert fødeinntak og økt opptak av visse forurensende stoffer (f.eks polyklorinertebifenyler). Laboratorie-eksponering for mikroplast viser negative påvirkninger som for eksempel vekstreduksjon i marine ormer og endringer i genregulering for fisk.

Det er manglende data på mikroplastkonsentrasjon i det norske miljø, og det er et behov for å vurdere omfanget av mikroplastforurensning langs kysten av Norge og Svalbard. Nivåene av menneskeskapte partikler (10-500 mikrometer) i Skagerrak virker lavere enn de som finnes i Østersjøen, men disse dataene er ikke omfattende nok til å konkludere. Det som er klart er at havhest (Fulmarus glacialis) spiser plast; nyere funn tyder på at 95 % av havhest i Nordsjøen har plast i magen, og at 58% inneholdt nivåer over 0,1 g som er identifisert som en av OSPAR-kommisjonens miljøkvalitetskrav. Fra norskekysten og spesielt Skagerrak er det funnet nivåer over 0,1 g hos 50 % av Havhestene som ble undersøkt.

1. Introduction

1.1. Plastics in general

Plastic is a generic term for man-made polymers that are most often prepared by polymerization of monomers from oil or gas. When not made from oil and gas, the polymer can be manufactured from coal, natural gasses, cellulose or latex from trees[1]. The molecular backbone of a plastic polymer is typically composed of hydrocarbons and other naturally occurring compounds. Other chemicals, additives, are also added to the polymer to provide desirable properties, such as plasticizers that are added to improve the malleability of certain polymers[2].

We now live in "a plastic world" where almost everything surrounding us is made of plastic, and it is hard to imagine a world free of this material. Plastic production has increased dramatically worldwide over the last 60 years, and is still increasing, with current production at around 300 million tons yearly (Figure 1)[3].

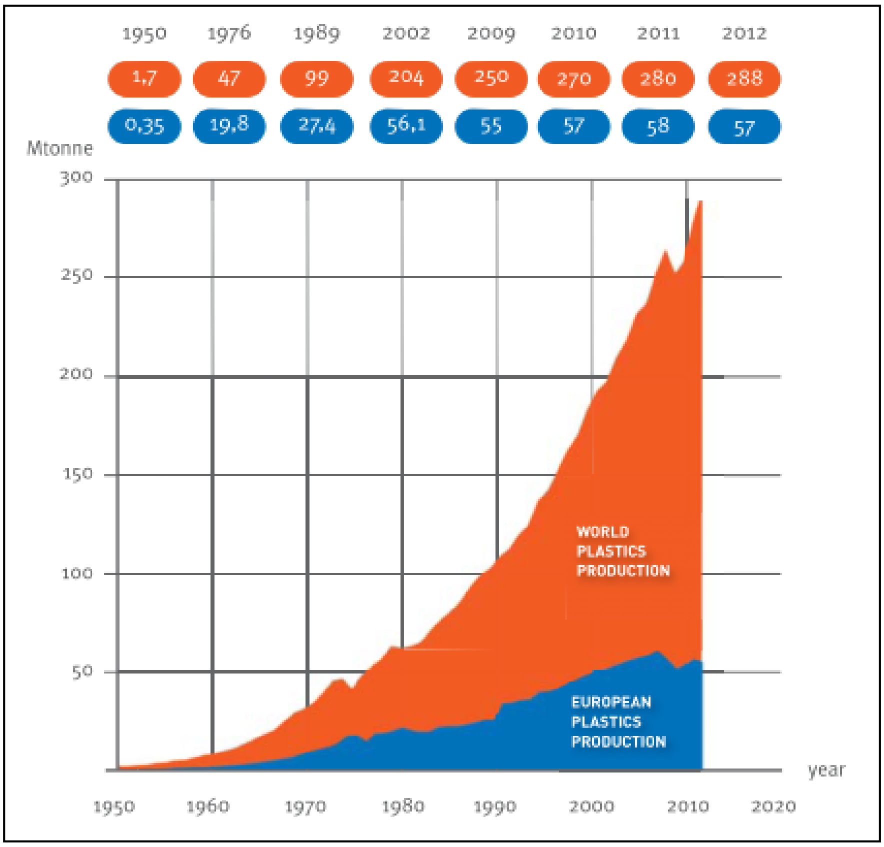

Figure 1. Total yearly plastic production. Not included PET, PA and polyacryl-fibers. Modified from Plastic Europe, 2013 [3].

The first polyethylene carrier bags were introduced in 1950 and by 2012 approximately 288 million tons of plastic was produced globally, with a turnover of over €300 billion. In Europe alone, 57 million tons of plastic was produced in 2012[3]. Polyethylene (PE) is the most common plastic type produced followed by polypropylene (PP) and polyvinyl chloride PVC (Table 1).

Table 1. The six most common plastic polymers produced worldwide in 2012 (Plastic Europe, 2013) [3].

Plastic type	**Abbreviation**	**x 10^6 tonnes**	**%**
Polyethylene	PE	85	30
High-density polyethylene	*HD-PE*	*35*	*12*
Linear low-density polyethylene and Low-density polyethylene	*LLD-PE, LD-PE*	50	*18*
Polypropylene	PP	54	19
Polyvinyl chloride	PVC	31	11
Polystyrene, Expanded-polystyrene	PS, PS-E	21	7
Polyurethanes	PUR	21	7
Polyethylene terephthalate	PET	19	7

Despite the many advantages of plastic, plastic litter can pose a serious threat to the environment. Around 50% of the plastic produced is used in low value products designed for disposable single-use[4]. The chemically inert nature of plastic makes it highly durable, a property that is often desirable. However, this is at the same time this becomes a challenge when plastic products are not properly disposed of or recycled and end up as litter. Exactly how long plastic can remain in nature is difficult to predict as there has been insufficient time to evaluate its true persistence. It is however known that most types of plastics persist in the environment for at least decades[5] and it has been estimated that between 60 and 80% of the world's litter is in the form of plastic[6]. Once plastic litter has entered a river it is carried downstream and often ends up in the sea[7] where a study that evaluated 3,070 samples worldwide found that as much as 88% of the open ocean surface contains plastic debris[8].

Different plastics have different fates once they end up in the sea based upon their physico-chemical properties (Figure 1). Most plastics are light materials with low density and many of the polymers will float in sea water (Table 2; sea water with a density of 1.02 - 1.03 (g cm^{-3}). The density of the given plastic material will determine the plastics buoyancy and where in the water column the particle will be, and thereby influence the possibility for interaction with different organisms[9]. For example PVC is negatively buoyant in seawater and will sink since it is denser than seawater (Table 2). Density is not the only factor that affects the buoyancy of polymers in the sea. Biofouling, the colonization of organisms on the polymer after it enters the sea, will also influence buoyancy and the ability of a light plastic material, for example polyethylene, to float (Table 2). Biofouling increases the weight of the plastic, thereby reducing its buoyancy, which results in light plastics such as polyethylene sinking when biofouled[10,11]. Fragmentation on the other hand does not affect buoyancy as there is no change in the density of the material.

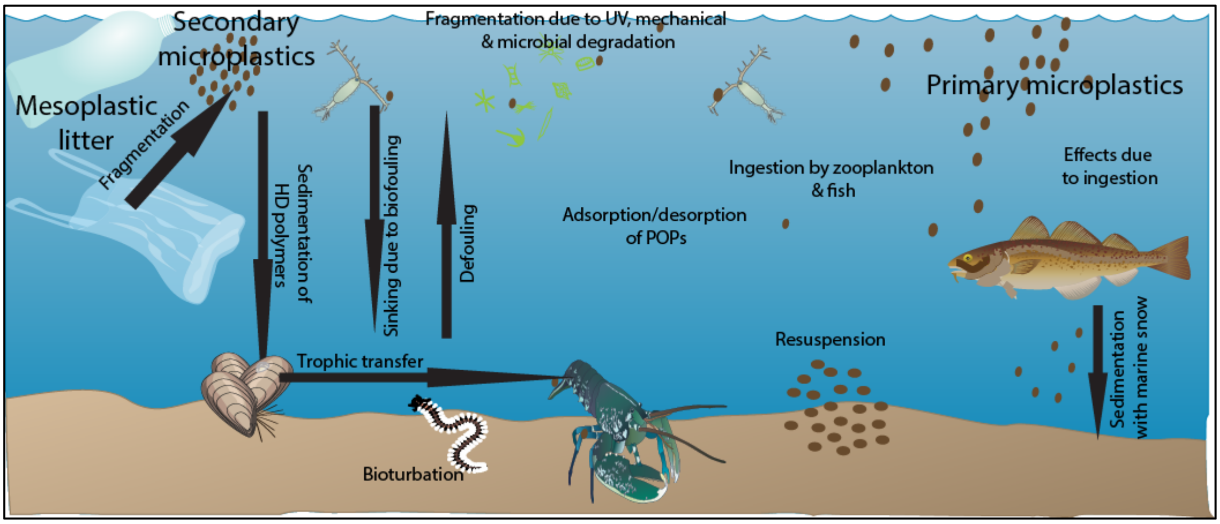

Figure 2. Potential fate and pathways and biological interactions of microplastics (Modified from Wright et al., 2013[9]).

Table 2. The density and buoyancy of the different plastic types.

Plastic type	**Density (g/cm^3)**	**Buoyancy (when clean)**	**Reference**
PE		+	
HD-PE	0.96	+	12
LLD-PE, LD-PE	0.925	+	12
PP	0.91	+	12
PVC	1.44	-	12
PS	1.05	-	13
PUR	1.20	-	http://www.dotmar.com.au/density.html
PET	1.38	-	14

* Seawater density: 1.02 - 1.03 $(g\ cm^{-3})$

There are two main sources of plastic into the marine environment; from maritime activities, such as commercial fishing and illegal dumping, and land-based sources such as river, storm water runoff, wastewater, inland litter blown to the sea and the litter people leave behind on beaches[15,16]. In heavily populated areas most of the plastic that ends up in the sea is thought to come from land-based sources[6]. Floating plastics have the potential to be transported via currents and other hydrodynamics processes. Currents beneath the sea surface can transport less buoyant plastics that are neutrally or negatively buoyant.

A significant number of species are known to be affected by plastic contamination[6], with severe consequences such as starvation due to ingestion, drowning by entanglement and sub-lethal effects such as a reduced ability to feed[17,18]. Over 267 species of marine organisms are known to be affected by plastic pollution; 43% of all marine mammals, 86% of sea turtles and 44% of all sea bird species, are known to be affected by plastic litter[19]. It can be expected that even more species are currently affected by plastic waste since plastic production has since then increased. For certain species almost all individuals contain plastic; for example 96% of north sea fulmars have been observed to contain at least one piece of plastic[20]. Organisms exposed to plastic litter are not only exposed to polymers but also the additives that they contain, which can leach from the plastic over time[21]. Additives are typically organic substances, predominantly esters that are added during production to modify the properties of the material[2]. Many of these additives are hazardous with over forty included on the Norwegian priority list of hazardous substances[21]. Additives have the potential to leach out into the environment as the littered plastic becomes more brittle and exposed to abiotic factors such as UV-radiation and mechanical forces, and thereby act as a source of pollutants[22]. Plastics can also accumulate Persistent Organic Pollutants (POPs) and other pollutants[23]. Laboratory studies have demonstrated the sub-lethal effects of microplastics and environmental contaminants co-exposed to marine organisms[24,25]. To what extent this can be an additional source to POPs exposure to marine organisms is not clear and it has been suggested to be of little impact[26].

Another less intuitive problem posed by plastic litter is the potential to transport invasive species. Many species, such as molluscs, bryozoans, barnacles, polychaete worms and hydroids can use floating debris as a habitat that, and will be transported along with the plastic[27]. Even a fish has been found to have been transported by debris within a plastic boat from the tsunami in Japan and made its way to the US (http://www.livescience.com/28468-live-fish-tsunami-debris.html). It has been estimated that the spread of fauna has doubled in subtropical areas and tripled in high latitude areas (above 50°) due to floating plastic debris[28].

2.2 Microplastic particles

Plastic particles < 5 mm in diameter were first scientifically in 1972 in the Sargasso Sea[29] but it was not until 2004 that the term microplastics was used and the significance of this phenomenon made apparent[30]. Since 2004 there has been a steady increase in the knowledge available about microplastic contamination in the marine environment [27] and this is reflected by the increasing number of publications on microplastics in recent years[31]. In addition to scientific interest, there is also a growing interest among citizens and NGOs to do something to avoid small plastic particles from further polluting the world's oceans.

There is at present a lack of standardization for the definition of plastic particle size (Table 3). This is urgently needed to enable comparisons of microplastics distribution and abundance across studies[32,33]. Browne (Pers. Comm.) argues that microplastics should be defined as particles measured in micrometer (µm), based on the established use of the prefix "micro" for measures of length by the International System of Units. Andrady [34] has suggested adding the term "mesoplastics" for particles >0.5 mm, but it is now frequently used for particles in size ranges above 5 mm with varying upper limits, e.g. 5-25 mm[35],5-50 mm[36]. At the lower end of the size scale the term "nanoplastics" is used to refer to particles in the nanometer range, i.e. <1 µm[34,37] but no specific size classification is currently available. These particles at molecular size have not yet been studied in marine environments, but they are likely present and may pose risks to ecosystem health[38].

Table 3. Size classifications of plastic litter.

Classification	size range	References
Mesoplastic	5000-50000 μm	[34–36].
Microplastic	1-10000 μm 1-5000 μm	[7,32,39–42]
Nanoplastic	<1 μm	no published definition

Microplastics can either enter the environment directly or following the breakdown of larger plastic. Microplastics, often referred to as microbeads, are manufactured at a microscopic size for use in cosmetics, such as exfoliators and toothpastes (Figure 3 (left), air blasting technologies for clearing surfaces like boats and machinery from rust and human medicine, serving as vectors for drug delivery[43–45]. When large plastic pieces become brittle or aged due to UV radiation, waves and other abiotic factors, they are slowly broken down into smaller and smaller pieces that eventually are <5 mm in diameter[9,37]. A third category of microplastic, which is often kept separate from the others, is "industrial plastic" which refers to resin pellets used as precursors in plastic manufacturing processes (Figure 4). These pellets are millimeter-sized and are therefore easily "lost" into the environment during processing and transport. Such lost pellets have been found on a range of beaches worldwide[31,35,46]. Synthetic materials are also heavily used in various consumer products that can shed synthetic fibers when they are washed. These fibers can enter the sea in areas with very basic or no wastewater treatment[9] or due to storm water overflow from wastewater treatment plants [47]. It is estimated that as much as 2.4 mg person^{-1} day^{-1} of microplastic is released into the environment from consumer products[48]. In the EU 70% of households are connected to wastewater treatment plants, however treated wastewater still contains microplastic particles at concentrations of up to 100 particles L^{-1} that can be released into the environment[47]. The breakdown of larger plastic items have been suggested to be the biggest source of microplastics to the marine environment[7].

Figure 3. Examples of microplastics from a personal care product (toothpaste on the left) and from the breakdown of larger plastic pieces (on the right).

Figure 4. Plastic pellets from manufacturing typically found on beaches.

The most common types of microplastics found in the environment are spheres, pellets, irregular fragments, and fibers[9]. Polyethylene is the most commonly produced plastic polymer (Table 1) and this is reflected in what is typically found in the environment. For example, barnacles collected from the North Pacific were found to contain 58 % polyethylene, 5 % polypropylene, and 1 % polystyrene microparticles[49].

Browne (Pers. Comm.) dedicates a section to sources and pathways of microplastics. He urges for a clear separation between "sources" and "pathways" and proposes four categories of sources:

1. Larger debris,
2. Cleaning products (cosmetics and airblasting),
3. Clothing (fibers)
4. Medicines.

The associated pathways can be different for these four:

1. Larger debris breaks down to ever smaller pieces through fragmentation and/or weathering, i.e. a reduction of molecular mass due to impacts such as physical abrasion against sediments, UV light, microbial degradation etc. Boring animals such as isopods may produce microplastics through their boring activities.

2. Cleaning products contain primary microplastics that enter terrestrial waterways through wastewaterwhere they cannot be filtered out due to their small size.

3. Fibers from clothing reach the sea via the same pathway when they are released into the sewage from washing machines, and to a lesser degree probably also via airborne contamination from land.

4. The pathways of microplastics applied in medical applications are to date unknown, but it can be presumed that also these particles eventually enter the sewage systems and are released into the environment that way.

Microplastics are difficult to remove once present in the environment, particularly marine environments. They escape the filtering systems of wastewater treatment systems because of their small size and enter rivers and ultimately the sea. It is at present virtually impossible to remove microplastics from the sea, e.g. using nets, without at the same time removing even more planktonic biomass and subsequently disrupting ecosystem functioning.

Microplastics are small enough to be ingested by many marine species, for example filter feeders ranging from plankton to baleen whales and basking sharks[50–53]. Sea birds are also very vulnerable to microplastic litter, especially floating plastics (both in the macro and micro scale) that is easily confused for prey like fish eggs and might therefore be eaten[27]. In addition, organisms breathing with gills, such as fish and crabs, as well as other filter feeders, such as mussels and barnacles, are also likely to be affected by microplastic. These various adverse effects on marine biota are discussed in detail in Section 4 below.

Ingestion of microplastics by species in aquacultures or fisheries may potentially pose a risk for human food safety [54] and excretion of microplastics in faces can result in its sedimentation and thus affect biogeochemical cycles and the food supply to the benthos.

Similar to macroplastic (Section 2.1), microplastics can also serve as a habitat for diverse microbial communities[28,55–57]. Colonized microplastics may be more attractive as food items than 'pure' plastic particles, and thus enhance ingestion by planktivorous predators and transfer up the food chain. They may also serve as transport vehicles for alien microbes, thereby facilitating introduction of non-native species. If these microbes are also pathogens, microplastics may become vectors of disease to the marine fauna[57,58].

In addition to damage from the microplastic particles themselves, microplastics, as with macroplastic, can contain additives and accumulated contaminants and may potentially be an exposure route of harmful chemicals. Microplastics can potentially be ingested by marine wildlife, and their small size and large surface area to volume ratio increases the contact area with the organism[25,59,60]. The role of microplastics to act as vectors for transporting POPs and PBT substances (persistent, bioaccumulative and toxic) already present in the environment through sorption to plastics have been suggested to be relatively small compared to other pathways[48], although concentrations of PCBs found on polypropylene pellets have been found to be over 100 times higher than the surrounding seawater[61]. Certain models have also suggested that plastics can reduce the accumulation of contaminants in the environment and their availability to organisms due to the sorbing nature of plastic[26]. Not surprisingly, weathering of microplastics in the environment appears to increase the contamination load[62].

2. Loads of microplastics in the environment

2.1 Occurrence, distribution and properties of microplastics

2.1.1 Water column

Microplastics are ubiquitous in the world's oceans and they have been found in both the Atlantic and the Pacific oceans and their adjacent seas, in both coastal areas and offshore (Table 4). The proportion of samples containing microplastics ranges widely, but most studies have found microplastics in the majority of the samples collected (e.g. 60%[63] in the northwestern Atlantic, 61% off Portugal[62], 74% around Corsica in the western Mediterranean[64], 89% in the Celtic Sea[65] and 97% in an estuary on the North Sea[66]). Concentrations of microplastics in water samples range from < 1 particle m^{-3} to several hundred particles m^{-3}, but measurements are inconsistent in terms of both sampling methods (device, mesh size and depth layer(s)) and units measured, highlighting the need for scientific conventions and standardizations with respect to sampling and quantification of pelagic microplastics. Fibers are often the dominant type of microplastics found[30,41], followed by granules and films[67].

Many studies to date have assumed that plastics float and therefore focused their sampling on the surface layer and neuston[27,52,64,68], which is defined as the organisms living on top of or within the uppermost layers of the water column, while other studies have confirmed the presence of microplastics also in sub-surface layers (e.g.[69]), down to a few meters depth. Microplastics distribution in deeper water layers has not been studied so far. The amount of microplastics recorded (abundance or weight) appears to also be influenced by the sea conditions at the time of sampling[64,65,70]. Concentrations of micro- and mesoplastics were recorded near Corsica in the Western Mediterranean with an average concentration of 0.062 particles m^{-2}, but were found with a maximum of 0.69 particles m^{-2} during periods when offshore winds were low[64]. It has been proposed that there is an inverse relationship between abundance of microplastics and wind speed, because microplastics get submerged into the mixed layer during high wind events and are then not picked up in surface tows[70]). In addition, microplastics can be negatively buoyant inwater (Table 2) and sink over time or alternatively start sinking upon microbial colonization increasing particle density [71].

Table 4. Comparison of pelagic microplastics measurements in the world’s seas. Note differences in abundance units (particles m^{-3}) and (particles m^{-2}).

Location	Average concentration	Average weight (mg m^{-2})	Reference
Northwest Atlantic (coastal)	3 particles m^{-3}		29
Northwest Atlantic (offshore)	67 particles m^{-2}		72
Northeast Atlantic (Celtic Sea)	2.46 ± 2.43 particles m^{-3}		65
Northeast Atlantic (Portuguese coast)	0.002-0.036 particles m^{-3}		73
	102000 particles m^{-3}		74
Western Mediterranean (Sardinia)	0.116 particles m^{-2}	0.202	68
Western Mediterranean (Corsica)	0.062 particles m^{-2}		64

Location	Average concentration	Average weight ($mg\ m^{-2}$)	Reference
Western Mediterranean	130 particles m^{-2}	58	36
Western Mediterranean (Central)	0.15 particles m^{-3}		52
Northeast Pacific (southern California)	8 particles m^{-3}		75
North Pacific (central gyre)	334.3 particles m^{-2}	5114	76
Northeast Pacific	0.004-0.19 particles m^{-3}	0.014-0.209	77
North Pacific subtropical gyre	0.021-0.448 particles m^{-2}		49
North Pacific subtropical gyre	>1000 particles m^{-2}		78
East China Sea	0.167 ± 0.138 particles m^{-3}		
Yangtze estuary	4137.3 ± 2461.5 particles m^{-3}		67
South Korea coast	13 ± 11 particles m^{-2}		79
Lake Hovsgol (Mongolia) [Freshwater]	20.26 particles m^{-2}		80

2.1.2 Beaches and sediments

Significant amounts of plastic litters beaches and the sea floor [6,81] and similar to the litter found in the water column, a large proportion of the debris on the sea-bed is often plastic (reviewed in[6]. For example, a study from Japan found that 80-85% of the debris on the sea floor was plastic[82] while plastic on beaches have been found to account for as much as 98% of the marine debris[62]. The number of particles found in sediments can be high with up to 2,420 particles m^{-2} (corresponding to 326 g m^{-2}) determined in samples from Portuguese coast (corresponding to 283 g m^2)[62] while in a worldwide study on the abundances of microplastic particles in sediment found between 2 (in Australia) and 31 (Portugal and the United Kingdom) particles 250 mL^{-1} of sediment[41]. When comparing these concentrations with those found in the water column caution must be used since the size definition used when studying microplastics in sediments seems often to be <1mm, contradictory to the more commonly definition of < 5mm when studying other parts of the marine environments (see Chapter 1.2).

In addition to finding plastic litter at beaches and costal sediments, microplastics have also been found in the deep sea[83]. Little is known about the spread of non- buoyant microplastics due to underwater currents but modelling the fate of pellets (~ 5mm) in such environments has been attempted. Tidal force was seen to impact pellet movement and episodic local events such as intertidal waves can increase the transport and spread of microplastics in association with the sediment, although the author highlights the need for more understanding and research upon this theme[84].

Considerable amounts of resin pellets in the size range 3-6 mm are typically found on beaches near industrial areas[62]. Data for microplastic pollution on beaches can also be gathered using unconventional methods that saves time and money, as demonstrated when schoolchildren from all over Chile documented the distribution and abundance of small plastic debris[85]. 85% of the plastic debris was between1 to 4.75 mm while the rest of the debris was between 4.75 to 10 mm with an average concentration of 27 items m^2. These concentrations are relatively similar to those found in Malta and

Russia[85]. In Malta the main plastic particles found on the beaches were pellets, but the source of these industrial pellets are not known[86].

Table 5. Examples of the level of microplastics found in sediments.

Area	Habitat	Year	Concentration	Units	Reference
Worldwide	Continental shelf	2004-2007		particlesL^{1} sediment * originally 250 ml sediment	41
E.g. Australia			8 (mean)		
E.g. UK			124 (mean)		
Belgium coast	Harbor	2011	390 (max.)	Particles kg^{-1} dry sediment	32
Malta (Mediterranean)	Beach	2011	36 (mean)	Particles m^{-2}	86
Canada (North Atlantic)	Intertidal sone	2012	~20 - ~80	Particles 10 g^{-1} sediment	87
Germany	Beach	2012	621 (max.) 14 (max.)	Granules 10 g^{-1}, and fibres 10 g^{-1}	88
Portuguese coast	Beach	2012	2397 (mean)	Particles m^{-2}	62
Chile (continental coast)	Beach	2013	30 (mean)	Particles m^{-2}	85

Microplastic contamination is not always linked to human activity (the more activity the more pollution) but there does seem to be an link between abiotic factors within enclosed areas such as harbors, where for example plastics would sink before leaving the harbor[32]. The types of particles found tend to reflect the most commonly used plastics. For example a study from Italy found the most predominant microplastics to be polyethylene (48%) and polypropylene (38%)[89], in line with the most commonly produced plastic polymers (Chapter 1.1; Table 1). Rivers appear to contribute significantly to the levels of pelagic marine microplastic in certain areas (e.g. Belgian coast[32]). In other locations where high levels have been reported it has been difficult to establish the source of the elevated microplastic concentrations.

Fibers are often the dominant microplastics found in sediments[32]. Care must be taken when evaluating such data since it is easy to contaminate samples with fibers as was seen in a study from Germany where they had to exclude fibers from the spatial comparison due to fiber contamination in the control sediment[90].

2.2 Marine Biota

Marine organisms are known to ingest microplastic particles (Table 6). Many commercially important marine organisms are known to contain microplastics with several possible routes for exposure; for example via the mouth and thereby the digestive system or via the gills. Ingestion of microplastics is well known and the digestive system is often examined when looking for the presence of microplastics[37]. Exposure via the gills has not been demonstrated in the environment, but as shown in Table 6 several suspension-feeding organisms have been reported to contain microplastics and this might be due to uptake over the gills. Laboratory studies have shown uptake over the gills in the Shore Crab[91].

2.2.1 Bivalves

Bivalves such as blue mussels are suspension-feeders that can filter as much as around 2 liter of seawater every hour[92] and therefore it is not surprising that they have been found to contain microplastics. Farmed blue mussels have been shown to contain more microplastics than wild mussles when collected from the same sites[87]. The higher levels of microplastics in the farmed mussels were largely assumed to arise from the plastic rope the mussels were grown on[87]. Another study of farmed blue mussels from Germany (North Sea) and farmed oysters from Brittany, France (North Atlantic Ocean), showed that both species contained microplastics; 0.36 ± 0.07 particles g^{-1} (wet weight) and 0.47 ± 0.16 particles g^{-1} (wet weight), respectively[54]. The significance of microplastic pollution on the safety of seafood is not known, although it is important to note that the concentrations determined in the farmed mussels and oysters are relatively small. If eating 250 g of blue mussels one will consume 90 particles, and 6 oysters of 100 g per the portion will contain around 50 particles[54]. Although, based upon the yearly consumption of shellfish in Europe the number increases to 11,000 particles $person^{-1}$ $year^{-1}$ [54].

Table 6. Examples of microplastics in wild organisms.

Organism	Species	Area	Ind. w/plastic (%)	Plastic particle per ind	Mean Size	Organ	Reference
Barnacles	*Lepas spp.*	North Pacific	33.5	1 to 30	1.41 mm	Gut	49
Farmed Blue mussels	*Mytilus edulis*	Germany (North Sea)		0.36 ± 0.07 particles/g tissue		WO	54
Farmed Oyster	*Crassostrea gigas*	France (North Atlantic Ocean)		0.47 ± 0.16 particles/g tissue			
Wild mussels	*Mytilus edulis*	Canada (The Eastern Passage)	100	170/5		WO	87
Farmed mussels	*Mytilus edulis*	West coast of Newfoundland and Labrador	100	375/5			
Lobster	*Nephrops norvegicus*	Clyde Sea	62		Round "balls"	Gut	93
Fish	*All*	English channel	36.5	1 to 3	1.0–2.0 mm	Gut	94
	M. poutassou		51.9				
	A. cuculus		51.5				
	M.merlangus		32				
	T. trachurus		28.6				
	T.minutus		40				
	Z.faber		47.6				
	C.lyra		38				
	C. macrophthalma		32.3				
	B.luteum		26				
	M. variegatus		23.5				
Fish	*All*	North Pacific Central Gyre	35	2,1	1.57 mg	Gut	50
	S. californiensis			7,2			
	M. aurolanternatum			6			
	L. interrupta			1			
	H. reinhardtii			1,3			

Organism	Species	Area	Ind. w/plastic (%)	Plastic particle per ind	Mean Size	Organ	Reference
	A. indopacifica			1			
	C. saira			3,2			
Fish		Brazil -South Western Atlantic (estuaries)		1 to 2		Gut	[95]
	C. spixii		18				
	C. agassizii		33				
Dolphins	*Pontoporia blainvillei*	Atlantic ocean	15.7		8.5 ± 7.5 cm	Gut	[96]
	Sotalia guianensis		1.3				

2.2.2 Crustaceans

Barnacles are sessile organisms also living in the intertidal zone. Like mussels they are suspension feeders and it is therefore not surprising that 33.5 % of barnacles from the North Pacific contain microplastic particles (Table 6). The average number of microplastic particles is typically between 1 and 30 [49]. In the Clyde Bay (West coast of Scotland) as many as 83% of lobsters (*Nephrops norvegicus*) found there have been reported to contain microplastic particles and that 62% of those particles were present as tightly tangled balls (Figure 5; [93]). Lobsters are omnivorous and thereby consume a lot of different benthic fauna such as crustacean, polychaetes, bivalves and the ingestion of plastic particles is likely to be either via food or passively from the sediment as they feed[93].

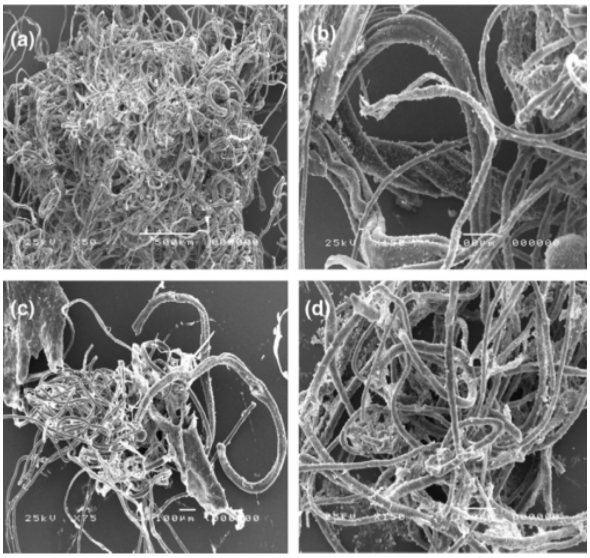

Figure 5. Scanning electron microscope (SEM) pictures of plastics found in *Nephrops norvegicus* (Clyde Bay, Scotland). Picture taken from Murray et al. 2011 [93].

2.2.3 Fish

Several fish species have also found to contain microplastic particles in their digestive system[50,94,95]. Published data suggests that overall around 30% of the individual fish examined contained microplastic particles (Table 6). A wide range of fish species has been examined and to our knowledge no species has yet to be reported as not having ingested microplastic particles (although there may be a bias in that findings of clean fish are not reported). Even though a large number of fish species have been examined to date, the spatial coverage of such studies is relatively poor with insufficient data to decipher any spatial trends. The number of microplastics found in the digestive system of fish is typically between 1 and 7.2 (Table 6). In the English Channel less dense polymers, such as polystyrene and LDPE (Table 2) were only found in pelagic feeding fish, however, less dense polymers where found in fish that fed in both pelagic and demersal waters. The plastics polymers found in the English channel are known to be used a lot in the fishing industry, which may be a possible source[94].

2.2.4 Other parts of the marine habitat

To our knowledge only one study is currently available on microplastics in sea ice. In the central Arctic ocean high concentrations of ice-entrapped microplastics, up to 240 particles m^{-3}, have been observed[97]. Microplastics consequently accumulate also in supposedly pristine marine environments in great distance from populated areas, also supported by the most recent results from Arctic fulmars (see sections 2.6.5 and 4.5). Polar sea ice may represent an important global sink of microplastics, both in the Arctic and Antarctica. With projected climate change and global warming more studies are required to assess the potential for significant microplastic contamination to the ocean as the ice melts.

2.3 Microplastics in Norway

We know little about plastic litter in general in the Norwegian marine environment, but we know enough to say that it is a problem. There are considerable amounts of marine litter found on beaches along the Norwegian coast and the coast of Svalbard[98]. Litter is a transboundary issue since around 50% of the plastic produced is buoyant and can be carried by the oceans across international borders. Microplastic pollution in the Norwegian marine environment is virtually unknown. A pilot study was performed in 2010 and 2011 investigating the occurrence of anthropogenic particles (between 10 and 500 µM) in Norwegian waters (in this case for the Skagerrak between Arendal and Hirtshals[74]. Microscopic litter (not separated as plastic particles) was found across the Skagerrak and a number of black and blue particles were found in addition to large amounts of fibers. The concentrations of particles were variable between October 2010 and November 2011. This could indicate yearly or seasonal variation as seen for other microplastic studies[15] but no specific concentrations of microplastic in the area were established. Due to a lot of uncertainties in the Skagerrak measurements the author claims it is not possible to compare Skagerrak and the eastern areas (Baltic Sea), but there are indices towards lower concentrations here than in Sweden, and there is an urgent need for more information about micoplastics in the Skagerrak area, along the Norwegian coast and around Svalbard. Studies on Northern fulmars (*Skagerrakus glacialis*) in the North Sea show that they contain large amounts of plastic; in a study from 2003-2007 as many as 95% of the birds from the North Sea had plastics in their gut with an average of 35 plastic particles per bird[99].

2.4 Properties of microplastics

Microplastics are found in a variety of shapes, structures and polymer types. For the North Pacific Moore et al.[76] reported thin films, polypropylene monofilament line and miscellaneous fragments in their samples. Product fragments <2.5 mm in size accounted for the majority of particles recorded in the study by Doyle et al. [77], followed by fishing net and line fibers, and industrial pellets. In the northwest Atlantic Morét-Ferguson et al.[71] found different proportions of plastic forms at different latitudes with the most diverse microplastics in the northernmost area (40°N), while lines were dominant contributors at latitudes with active fisheries (15 and 40°N). Fragments were major constituents in all locations, whereas industrial resin pellets made up a high percentage (38%) of particles only at 20°N. A qualitative analysis by Faure et al[36] in the western Mediterranean similarly revealed a dominance of fragments (77% in mass), but also thin films (13%), foams (7%), pellets (2%) and lines (2%). Lusher et al.[65] reported 96% polyester and nylon fibers in the Celtic Sea (excluding cellulosic Rayon from the counts), while no virgin resin pellets were found. The most important polymer-types include typically those found in clothing, packaging and other consumer products, but also from fishing gears and boat pains. Frias et al.[73] found polyethylene (PE), polypropylene (PP) and polyacrylates (PA) along the Portuguese coast. Alkyds and poly(acrylate/styrene) accounted for 81 and 11%, respectively, of the total polymer content of the surface microlayer samples off south Korea[79].

2.5 Spatial and Temporal trends

2.5.1 Spatial trends

To measure microplastic concentrations at different sites is important to assess the spatial scales at which microplastics enter, travel and accumulate in the marine environment. It took only a few decades for plastic debris to reach oceanic habitats from pole to pole: they are found in the open ocean, on shorelines of even the most remote islands and in the deep sea, since mass production of plastics began in the 1950s[7]. At global scale several studies identified large-scale convergence zones of plastic debris due to the major ocean currents[100]. High concentrations of microplastics were first found in the North Pacific central gyre [76] and the term "ocean garbage patches" has since been coined[101–103]. Martinez et al.[100] describe the processes by which debris gets "trapped" in large-scale oceanographic features using surface circulation estimates in combination with Lagrangian trajectories of debris for the south Pacific subtropical gyre. Law et al.[63] defined an accumulation zone (25 to 41°N, 130 to 180°W) in the North Pacific subtropical gyre and estimated a minimum of 21,290 tonnes of floating microplastic in this area. A modelling study has identified a total of 5 ocean gyres (garbage patches) on our planet (North Atlantic, South Atlantic, South Indian, North Pacific and South Pacific), and in addition predicts a hitherto unreported patch in the Barents Sea[104]. These patterns are confirmed and summarized in a study by Cozar[8], see Figure 6. The great spatial heterogeneity of microplastics at large and mesoscale (10s of km) makes it difficult to extrapolate local monitoring data to larger areas[49].

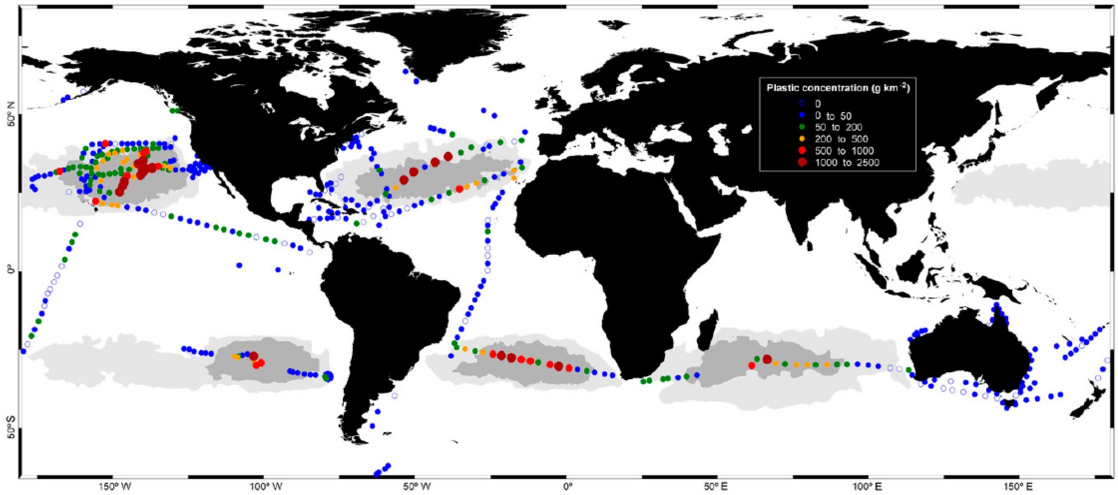

Figure 6. Spatial trends in the world oceans of plastic debris (Cozar et al., 2014) [8].

More locally, Browne et al.[105] found spatial patterns of microplastics along an estuarine shoreline (English Channel, UK), where proportionately more microplastics were deposited downwind, in habitats with slow-moving waters. High spatial variability was found in the western Mediterranean[52,64,68], with higher concentrations of microplastics offshore than coastal, while no distinct spatial pattern was found in a coastal area off South Korea[79].

2.5.2 Temporal trends

Measurements over time are important in order to know whether the concentrations of microplastics in the ocean are increasing or decreasing. An increasing amount of microplastics is likely to reflect an increasing amount of plastic litter released into the environment. Although many other factors can affect the formation of microplastics, such as uneven breakdown of already existing plastic litter due to change in climate, increased turbidity on the ocean floor etc. Temporal data can also be used to measure the abundance of different types of plastic litter (both micro- and macroplastics) over time such as industrial plastic waste contra commercial plastic waste. This knowledge can be used to estimate which sources are the biggest problem (by discharging more or less over time into the environment). As for other environmental concerns such as climate change or chemical pollution it is useful for stakeholders to look at trends over time to choose which action is needed to reduce the effects on the environment.

Very few long-term surveillance studies have been reported on the occurrence of microplastic as it is a relatively new area within marine research. As highlighted earlier a lack of standardization makes it difficult to compare data between studies due to slightly different methods used (can also be subjective differences), and also different units of measurement are used, as well as different use of the definition of microplastics (see more in section 2.2). Another factor to consider when interpreting results of microplastic analyses in the water phase, is the hydrophobic characteristics of polymer that results in an extreme heterogeneous distribution in water, and therefore water samples from different times and areas need to be from a similar type of water body to be comparable[15].

2.5.3 Beach litter

The Convention for the Protection of the marine Environment of the North-East Atlantic (OSPAR) commission monitors beach litter on selected beaches. Beach surveys are time efficient and little logistical planning is needed, it is also relatively cheap since voluntaries often contribute with data when cleaning beaches[37]. By repeating the beach cleaning on the specific beach every year, preferably same time of year due to known seasonal variations (e.g. more debris during the winter than during the summer;[106] accumulation of plastic debris can be monitored over time[15]. For example a beach survey on Bird Island, a remote island in South Georgia (Antarctic), found an increasing number of items (debris) from 1990 to 1995 [106]. Another survey of beaches in South Africa found the same increasing trend[107].

2.5.4 Sediment

A study of the Belgium coast investigated different sediment layers looking at temporal trends. Each layer of 8 cm represented a three years period. An increasing trend of microplastics (<1 mm) with time (Figure 7) was observed, matching the increasing plastic production worldwide (Trend line in Figure 7).

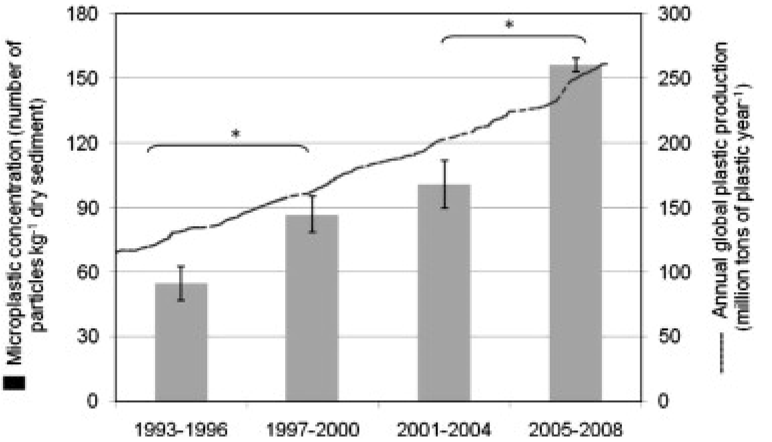

Figure 7. Temporal trends in microplastic particle (<1mm) contamination in sediments (Claessens et al., 2011) [32]. The trend line shows annual plastic production worldwide (Plastic Europe, 2008).

2.5.5 Water column

The same trend with increasing amount of macro and microplastic litter is also found in the water phase; debris found (not size defined) in the North Pacific Subtropical Gyre the plastic concentration measured to be 335,000 items km^2 (5.1 kg km^2) in 1999 was one order of magnitude higher then measured in the 1980 [15,76]. Also a long-term study of microplastics from 2004 [30] measured microplastics from old plankton trawls (samples taken between Aberdeen and Shetland from the 1960s and up to 2000), found microplastics in samples from all years and also found the concentration of microplastics to increase by time. However another long-term study (North Atlantic Subtropical Gyre) found particles of around 1 mm in size in 60% of all plankton net trawls between 1986 and 2008, but no increasing plastic concentration over time was seen[63].

2.5.6 Sea birds

In 2013 OSPAR decided to use ingestion of microplastics in Northern Fulmars as indicators for the Greater North Sea area. Northern Fulmars eat litter floating on the sea surface, mistaking it for food and are therefore a suitable bioindicator for plastic abundance in the marine environment[108]. A trend seen in fulmar stomach is a shift from industrial plastic products to the occurrence of consumer plastics[15,99]. Although many studies have found increasing temporal trends of microplastics in the environment, it has been found in the Northern Fulmar that the total mass of plastic ingested has decreased[99] while another study on Common- and Thick-billed Murres (*Uria aalge and U. lomvia*), showed no increase in the presence of microplastics in their stomachs between1985 – 2012[109]. These studies reflect the need for long-term studies to understand the temporal change in the microplastic occurrence worldwide.

2.6 Where is all the "missing" plastic?

An important consideration when evaluating the impact of any type of pollution is to attempt to balance the quantities discharged with those measured. That is to compare the predicted microplastic particle concentrations with the measured ones. There has for a long time been a need for precise and accurate methods to determine plastic pollution in the environment[30] and this is still proving a major challenge[9]. Recently there has been an attempt to estimate the current load of plastic present in the ocean based upon 3,070 samples collected from around the world[8]. Cózar and co workers[8] estimated that the amount of plastic in the open-ocean surface is between 7,000 and 35,000 tonnes spread over 88% of the samples collected; the remaining 12 % contained no measurable microplastic but this is not to say that they were free of all plastic particles since particles smaller than measureable by the techniques used may have been present. In the same study they also predicted that over a milllion tonnes of floating plastic has been released into the open ocean since the 1970s and highlights a 100-fold difference between measured and predicted loads. This important study both highlights an important gap in the size distribution of floating plastic debris, but also hypothesise that there is substantial loss of plastic from the ocean surface. Possible explanations for this disparity that are proposed are the following sink mechanisms:

- Selective washing ashore of mm-sized fragments- unlikley

- Increase in rate of solar-induced fragmentation- unlikely.

- Gap in size distribution below 1 mm could indicate a fast breakdown of plastic fragments from mm to µm scale- likely.
- Preferential submersion of small-sized plastic with high surface:volume ratio and reduced buoyancy due to biofouling- likely.
- Ingestion by marine organisms and subsequent defecation- likely.
- As yet unidentified sink processes- likely.

It is likely that a multitude of processes are responsible for this disparity. As far as we are aware there has been no study to date to evaluate the uncertainties associated with the relatively few samples collected (3,070) when compared to the global sea-surface area as well as the uncertainties associated with the measurements made. It is also likely that the fragmentation process continues down to the nano-scale and has yet to be quantified. Establishing the fate of plastic in the ocean is an urgent matter since emissions into the ocean will continue and probably increase.

3. Hazardous substances in plastic

3.1 Additives in general

Additives are typically organic substances added during the production of plastics to impact the properties of the plastic material[2]. Over 300 different plastic additives were reported in 2000[110]. These additives can be divided into several groups (Table 7).

Table 7. Groups of plastic additives with examples of hazardous chemicals (Data from Deanin 1975 and Hansen et al., 2013) [21,111].

Additives	**Comment**	**Examples of hazardous additives**
Plasticizers: Phthalates Phosphates Epoxidized Esters Linear Aliphatic Esters Polyesters	High molecular weight Improve flexibility and durability Used in concentrations of 10-80% w/w or more of the total plastic composition	Diisoheptylphthalat (DIHP) Benzyl butyl phthalate (BBP) Bis (2-ethylhexyl)phthalate (DEHP) Bis(2-methoxyethyl) phthalate (DMEP) Dibutyl phthalate (DBP) Diisobutyl phthalate (DiBP) Tris(2-chloroethyl)phosphate (TCEP)
Reinforcements	For example glass (can account for 10-50 % by weight)	
Fillers	Up to 50% w/w. Inorganic mineral powders; Calcium carbonate, talk, clay, zinc oxide, glimmer, metal powder, wood powder, asbestos, barium sulphate, glass microspheres, silicious earth	
Flame Retardants	Concentrations are often 10-20% w/w. Three groups: organic non- reactive, reactive; inorganics Organophosphorus compounds; halogenated esters, heavily brominated or chlorinated organic compounds.	Short and medium chain chlorinated paraffins (SCCP-MCCP): Boric acid Brominated flame retardants Tris(2-chloroethyl)phosphate

Additives	**Comment**	**Examples of hazardous additives**
Stabilizers Halogen Stabilizers Antioxidants Ultraviolet Absorbers Biological Preservatives	Added between 0.1 to 10.09% by weight. Phenolic antioxidants are used in low amounts and phosphites in high.	Arsenic compounds Organic tin compounds Triclosan Barium-Cadmium-Zinc-Epoxy-Phosphite Bisphenol A (BPA); Cadmium compounds Lead compounds Nonylphenol compounds Octylphenol
Curing agents	0.1-2% w/w typically. Peroxides and other crosslinkers, catalysts, accelerators.	4,4'-Diaminodiphenylmethane (MDA) 2,2'-dichloro-4,4'-methylenedianiline (MOCA) Formaldehyde Depends
Colorant Inorganic Organic	Most often inorganic pigments. Often 1 – 4 % w/w.	Titanium dioxide Camium compounds Chromium compounds Lead compounds Cobalt(II) diacetate
Coupling agents	Often low concentrations. Combine the ingredients together. Act as a bridge between the polymer and the filler.	
Processing Aids Lubricants Other Processing Aids Flow Controls	Lubricants: Calcium, zinc, and lead stearates, petroleum and polyethylene waxes, and fatty esters and amides. Other Processing Aids; plastisol viscosity depressants, mold release agents, antiblocking (slip) agents, antifog agents	
Antistats	Used for making the product less static. Amines, quaternary ammonium	

Additives	Comment	Examples of hazardous additives
	compounds, organic phosphates, and polyoxyethylene glycol esters.	

The molecular size is a key property of the additive when evaluating how fast it migrates through and out of the plastic. The smaller the additives, the faster they will migrate[110]. A Norwegian Environment Agency report from 2013[21], reviewed the hazardous substances present in plastic material (Table 7). They found that 43 of the substances used in plastic material are listed in the Norwegian priority list of hazardous substances. In addition to phthalates, which can account for 10-70% w/w of a plastic, they also listed the following hazardous substances; brominated and phosphour organic flame retardants, stabilizers, heat stabilizers (0.5-3 % w/w); biocides (0.001-1 3 % w/w) and colorants (0.001-10 % w/w) (Table 7). Plasticizers are additives that make the plastics flexible and durable (Table 7) with two main types of; internal plasticizers and external plasticizers. The main difference is that internal plasticizers are added while processing the polymers and therefore it is incorporated into the plastics, while external plasticizers are added after polymerization and thereby is not that bound to the plastic material as internal plasticizers. When plasticizers are added to inflexible plastics they become more flexible. External plasticizers also impact the flexibility of a rigid plastic, but they react only with the parts that affect the flexibility and do not alter the chemistry of the polymer [110]. The external additives are more likely to migrate within the plastics and maybe also into the environment the internally plasticizers[110]. The plasticizers are most important as softeners for hard plastic material, and over 90% of all additives are used in conjunction with PVC[110]. PVC is denser than seawater (Chapter 1.1; Table 1) and will therefore sink. It is likely to assume that most PVC particles, if not ingested, will be found on beaches or in sediments and since we know that PVC contains the most additives, it can be a substantial source of plasticizer to the ocean floor. Phthalates, the most common plastic additive, has for a long time been known to be found in water, sediment, air, and biota[112]. As external plasticizers the phthalates are not chemically bound to the plastic material and can therefore migrate, leak or evaporate from the PVC material and into the media which surround it[113].

3.2 Chemicals found in plastic particles in the environment

3.2.1 Contaminants and additives reported in field-sampled plastic particles

A number of studies have demonstrated the presence of chemicals sorbed onto microplastic after a certain amount of time exposed to the marine environment. These studies fall into two categories;, those that are based on exposing microplastic particles in the marine environment and those based on the collection of particles found in the environment. Passive sampling based on the use of polyethylene [114] can also provide information on the type of chemicals that have been found to absorbed into polyethylene when exposed to seawater.

In the "Pellet watch" programme, where plastic pellets found on beaches are analysed for the presence of contaminants, PCB concentrations in pellets from beaches around the world were found to be spatially different; the coast of US had the highest, then Japan before Europe. Australia, tropical Asia and southern Africa had much lower concentrations. These findings reflect the PCB usages in the specific country, for example as much as 50% of all PCB produced globally is used in the US[115]. These data therefore confirm that plastic in the marine environment interacts with the POPs that are present.

Other contaminants found sorbed to plastic particles include hydrophobic chemicals generally found at very low concentrations in seawater but that tend to concentrate on plastic material. A summary of contaminants found sorbed to plastic pellets and debris is shown in Table 8. Substances that have received much attention include persistent organic pollutants such as polychlorinated biphenyls (PCBs), the insecticide DDT and its degradation product p,p'-DDE, as well as hexachlorocyclohexane isomers (HCHs). Other anthropogenic chemicals that have been detected in environmental plastic particles include polycyclic aromatic hydrocarbons (PAHs). In recent years, an increasing number of studies have reported levels of contaminants associated with plastic particles collected in the marine environment. In a majority of cases these particles have been collected from beaches and the plastic particles were mostly polyethylene and polypropylene, in agreement with production volumes (Table 1). Measurements based on open sea samples and plastic found in the gut of organisms have also been reported (e.g.[116]).Depending on the study, the size of the plastic particles and debris collected for contaminant measurements is not always reported or can vary significantly. The identification of chemicals and additives present sorbed to plastic particles and the subsequent measurement of their concentration level is important for the assessment of the risk that these particles pose to marine organisms, but are also relevant to the assessment of the potential for plastic particles to influence the distribution and movement/fluxes of contaminants at local and global scales. It also becomes important to assess whether chemicals found on plastic were originally present as additives or whether they have accumulated during particle exposure to the environment. For additives, concentrations in plastic particles are likely to be initially much higher than those that could be achieved through sorption from seawater. For example, the observation of decabromo diphenyl ether (BDE209) concentrations close to 10 000 ng g^{-1} plastic is most likely the result of its use as an additive rather than uptake from seawater[117].

Table 8. Reported contaminant concentrations in plastic particles collected in the marine environment.

Contaminant	**Range of concentrations (ng g^{-1} plastic)**	**References**
Polycyclic Aromatic Hydrocarbons (PAHs)	1-24,364	[23,117–120]
Polychlorinated Biphenyls (PCBs)	1-5,000 (18,600, 18,700)	[23,29,61,117–119,121–123]
Dichlorodiphenyltrichloroethane and related compounds (DDTs)	0.16- >1,000	[61,115–119,123]
Polybrominated diphenyl ethers (PBDEs)	0.3-9,909	[115,117]
PBDE 209	0.1-9,907	[117]
Hexachlorocyclohexane isomers	<2-36	[23]
Chlordanes (+ oxychlordanes)	4.29-14.4	[116]
Cyclodienes	2.41-50.9	[116]
Mirex	6.48-14.6	[116]
Hopanes (natural substances)	2,000-61,000	[124]
Aliphatic hydrocarbons	1.1-8,600	[118]
Hexachlorobenzene	12.4-17.5	[116]
Nonylphenols	0.7-3,936 (16,000)	[61,117,125]
Octylphenols	0.1-154	[115,117]
Bisphenol A	0.2-730	[117,125]
Perfluorinated compounds (PFCs)	0.011-0.116	[126]

The first polystyrene particles observed by Carpenter et al.[29] found that they contained PCBs at a concentration of 5 μg g^{-1}, presumably absorbed from seawater. Gregory et al.[127] also reported the presence of PCBs sorbed to colored polyethylene pellets found in sediments from the New Zealand coast. Polypropylene resin pellets collected from Japanese beaches facing the Pacific Ocean and the Sea of Japan and in Tokyo bay have been shown to contain not only PCBs, but also *p,p'*-DDE a degradation product of the insecticide DDT and nonylphenol[61]. Concentrations of PCBs and *p,p'*-DDE in polypropylene were apparently of a similar order or magnitude as Tokyo Bay sediments while nonylphenol concentrations were significantly higher. The authors conducted a field adsorption experiment that demonstrated that PCBs and p,p'-DDE were most likely sorbed from seawater, while nonylphenol was thought to be polypropylene additive-related [61]. Endo et al. [121] studied the variability in PCB concentrations in beached pellets from Tokyo. Analysis on an individual pellet basis showed relatively variable concentrations (< 28 - 2300 ng g^{-1} plastic) that appeared positively related to pellet discoloration. Relative differences in PCB concentrations in plastic pellets collected from different areas were in agreement with those observed in mussels. PE and PP particles collected from Californian and Hawaiian beaches in the Pacific Ocean as well as from stomach of Albatross birds (Guadalupe Island) were analysed for aliphatic hydrocarbons, PAHs, PCBs and DDT compounds[118]. When above limits of detections, aliphatic hydrocarbon, PAH and PCB concentrations were in the range 1.1-8600, 500-6200 and 27-980 ng g^{-1} plastic, respectively. The sum of DDTs reached a concentration over 1000 ng g^{-1} for pellets collected from the San Gabriel River (California). Fluoranthene was the PAH generally found in highest concentrations and this is in agreement with the relative distribution of PAHs generally found in polymeric passive samplers and in other microplastic monitoring studies[73]. Colabuono et al.[116] also assessed the occurrence of chlorinated compounds such as PCBs, hexachlorobenzene, chlordanes, cyclodienes, DDTs and Mirex sorbed to plastic pellets and fragments found in the digestive system of albatrosses and petrels. In addition, Teuten et al.[115] reported plastic debris concentrations for PBDEs, octylphenol, nonylphenol and bisphenol A. For most of these chemicals, concentrations varied over more than two orders of magnitude. Reported sums of concentrations of PBDE congeners (19) were from 0.4 to 57 ng g^{-1}. A recent study by Llorca et al.[126] reported concentrations of certain perfluoroalkyl chemicals sorbed to plastic particle collected on the Greek coast.

The number and types of chemicals that have been reported sorbed to plastic pellets (Table 8), particles and debris is relatively low considering the number of plastic additives used and contaminants present in the marine environment, however this may be due to the limited number of studies performed to date and the limited focus of the analyses performed. Most of the chemicals identified and quantified in plastic debris are relatively hydrophobic with logarithm of octanol-water partition coefficient (K_{OW}) over three and many of them have been classified as persistent chemicals.

3.2.2 Relationship between contaminant concentrations in plastic and in the marine environment

The potential for the sorption of a multitude of contaminants to plastic particles and debris from seawater means that contaminant concentrations measured in polyethylene or polypropylene particles (two of the most often found plastic debris) may reflect environmental concentrations the particles have been exposed to. Alternatively, concentrations measured in the environment may enable an estimation of contaminant concentrations in microparticles for further assessment of the risk of these concentrations and of contaminant fluxes associated with plastic particle transport (e.g. with ocean currents/rivers). Most of the concentrations reported above have been measured in particles in the millimeter size range. Since the microplastic range extends to micrometer particle sizes that are challenging to sample and for which contaminant concentrations cannot easily be measured today, the possibility to infer contaminant concentrations in the microplastic polymers from environmental concentrations may prove useful.

The generally good agreement between PCB concentration on polyethylene pellets collected from 30 beaches of 17 countries with data from global mussel watch programme has led to a proposal that the International Pellet Watch programme is used for the global monitoring of POPs in the marine environment (http://www.pelletwatch.org/maps/)[23]. The levels of PCB and DDT in the pellets was between 5 and 605, and 2 and 777 ng g^{-1}, respectively. The ratio of DDT and degradation its products indicated recent use of DDT in specific parts of the world (e.g. in Vietnam or Brazil). Concentrations of HCH isomers varied from below limits of detection (< 2 ng g^{-1} PE) to 36 ng g^{-1} polyethylene for coastal areas of South Africa. Hopanes were measured in some cases above limits of detection and reported concentrations between 2 and 62 μg g^{-1}. Finally total PAH concentrations were shown to vary over more than two orders of magnitude from 99 to 24364 ng g^{-1} for polyethylene pellets from Portugal. Heskett et al.[122] measured the concentration of chlorinated compounds found in plastic resin pellets sampled in remote areas of the Atlantic, Indian and Pacific Oceans as well as in the Caribbean Sea. Concentrations measured are representative of remote regions with POP concentrations at background levels. However, the reasons for measurements in some cases of significantly higher concentrations need to be asserted. A long-term study of contaminants associated with beached pellets in the size range of 2 to 20 mm collected from South African beaches by Ryan et al.[123] showed generally decreasing trends in PCB, DDT and HCH concentrations in these PE pellets. As part of the international pellet watch initiative, plastic pellet-associated PAH, PCB, DDT, HCH and hopane concentrations were reported by Mizukawa [124] for plastic pellets collected from beaches of Portugal. Pellet-associated PCB concentrations were an order of magnitude higher for plastic collected from beaches in Porto and Lisbon than those from rural sites, potentially indicating that plastic pellets can indeed be representative of environmental concentrations of the environment they were collected from. This is also supported by further data from the Portuguese coast where higher concentrations of contaminants were found for pellets collected in industrial, urbanized area and harbors[62]. Karapanagioti et al.[119] sampled plastic pellets from beaches in Greece and analysed them for a range of hydrophobic contaminants (DDTs, HCHs, PAHs and PCBs). Difference in concentrations found at the different sampling sites were in agreement with known contamination levels at these locations, further emphasizing the possibility to use plastic pellets for global contaminant monitoring in the sea. Hosoda et al. [128] sampled plastic pellets on 11 beaches along the coast of Ghana. An electric waste disposal facility was identified as a major source of PCBs. Alkylbenzenes were also measured on plastic pellets and the authors proposed that plastic burning was responsible for high levels of triphenyl benzene. Urban areas were characterized by higher pellet-associated PAH concentrations. Endo et al. [121] studied the variability in PCB concentrations in beached pellets from Tokyo. Analysis on an individual pellet basis showed relatively variable concentrations (< 28 -2,300 ng g^{-1} plastic) that appeared positively related to pellet discoloration. Relative differences in PCB concentrations in plastic pellets collected from different areas were in agreement with those observed in mussels. Fisner et al.[120] sampled beached plastic pellets from 30 locations within 5-6 km stretch in Santos Bay (Brazil). They showed a high variability in PAH concentrations for a relatively narrow stretch of coast. This means that care is needed when attempting to infer on spatial and temporal trends in contaminant levels in the marine environment from beached plastic particles. The question that can be asked is what is the concentration measured representative of? For a valid assessment of spatial and temporal differences in contaminant concentrations in the marine environment through plastic debris and microparticle-associated contaminant concentration measurements, an understanding of factors affecting the uptake of contaminant from seawater into the polymers as well as knowledge of particle-to-particle variability from single coastal locations are needed. Further standardizing to a type of polymer may help reduced the variability that can be observed. Finally, the trajectory and exposure time of a plastic pellet in the marine environment is generally not known and although dispersion models can be applied to estimate the path for the particles, this will clearly add further uncertainty in the data. Zarfl and Matthies [129] attempted to assess the risk of plastic particles being a significant mode of transport of plastic-sorbed contaminants to the Arctic. The authors calculated fluxes of plastic particle-bound chemicals to the Arctic to be two to four orders of magnitude lower than those associated with ocean currents and five orders of magnitude lower than atmospheric currents. Contaminant concentrations in microplastic have been estimated from literature data for contaminant concentrations in sub-polar seawater and polymer-water partition coefficients. These calculations, however, do not take into account the smallest microparticles sizes. This means more information on the actual levels of microplastic, throughout the entire range of particle sizes, in seawater is needed to refine these estimates. In addition for chemicals that adsorb rather than absorb to the polymers, estimates should be based on surface area-based data rather than mass or volume-based amounts of plastic transported. Nonetheless, this mode of transport may be significant for substances that do not necessarily demonstrate possibility for long-range transport through other more common transport processes.

3.3 Processes and factors affecting the transfer of organic contaminants to and from (micro) plastic particles

Chemical additives present in microplastics (originally added in sometimes significant quantities during production) have the potential to be released upon discharge of these polymeric particles into the marine environment. As shown in Section 3.1, once released into the marine environment, microplastic particles also provide an inert phase for the sorption of trace contaminants present in water, sediment or biota. The rate and extent of exchange of chemicals between microplastic particles and the marine environment depend on (i) the concentration gradient that exist between the concentration of the chemical in the microplastic particles and the environment, (ii) the matrix in which the microplastic particles are present (water, sediment or biota), (iii) the physical and chemical properties of the polymeric particles, i.e. the supermolecular structure of the polymer (including the size of the microplastic particles) and of the chemical itself and (iv) the physical processes responsible for the degradation and erosion of the polymeric particles once they have entered the marine environment. For transfer to occur between two phases, a gradient between the chemical activity of the substance in the plastic and in the environment must exist. The range of concentrations at which chemicals are generally added to the plastic is sufficiently high to ensure such a gradient of concentration is present and the transfer of the chemical to the environment. On the other hand, microplastic particles initially free of contaminants present in the environment can sorb these contaminants over time.

Table 9. Processes and factors affecting the transfer of organic contaminants to and from plastic microparticles.

Processes/factors	**Description**
Concentration gradient	A gradient of contaminant concentration is needed for transfer to take place
Sorption process	Adsorption to specific adsorption site on the polymer (condensed and crystalline regions) often described by non-linear freundlich isotherm; absorption into the polymer matrix (for amorphous regions) generally described by linear isotherm and a polymer-water partition coefficient; covalent binding of the additive within the polymer during production
Contaminant characteristics	Hydrophobicity; molecular volume; ionization state; molecule shape and flexibility can affect sorption and diffusion coefficients
Type of polymer	Glassy versus rubbery polymer (with reference to glass transition temperatures, T_g), degree of cross-linking, polymer crystallinity and aromaticity
Size and conformation of microplastic particles	Diameter/size and surface-to-volume ratio
Polymer degradation and erosion	Changes in surface roughness, particle shape, release of chemicals upon polymer breakdown; formation of smaller particles with increased additive release rates
(Bio)fouling	Algal and bacterial growth that can modify transfer from polymer to water (and vice versa); contaminant biodegradation
Water turbulences and boundary layer	Water boundary layer at the surface of the particle affecting contaminant transfer (by diffusion) in the microplastic-water system
Temperature and salinity	Salting-out effect of hydrophobic contaminants with increasing salinity, i.e. decrease in water solubility with increasing salinity; Decreased solubility with decreasing water temperature (i.e. increased distribution coefficients between the polymer and water)
Ingestion	Digestive fluids and direct contact that can enhance mass transfer to and from the microplastic; Gut residence time

Processes/factors	Description
Sediments	The presence of sediments and dissolved organic matter in the vicinity of microplastic particles can substantially modify contaminant exchange kinetic between the microplastic and its surrounding environment. Sediment porosity and organic carbon content can also affect transfer of chemicals to/from the microparticles

The kinetic rate of release of the chemicals from the plastic will depend on the size and conformation of the microplastic particle. The surface-to-volume ratio of the particle is a crucial factor dictating the exchange kinetics of chemicals between polymers and water[7]. Modelling studies have shown that dissipation half-lives of toluene, o-xylene and tetrachloroehtylene from rubbery plastics are expected to increase with increasing radius of spherical microplastics[115]. Based on the experience obtained through passive sampling, the rate of uptake or release of hydrophobic chemicals into polymers such as PE or silicone rubber is highly dependent on water turbulences around the polymeric sampler[130]. With increasing water turbulence, the diffusive boundary layer formed at the surface of the polymer becomes thinner, reducing the diffusive path for uptake into the polymer. After a certain period of exposure in water fouling of the surface of the polymer may affect the exchange of chemicals between the polymer and water. The exchange of chemicals between polymers and sediments is more complex since chemicals can transfer through pore water but also from direct contact of sediment particles and dissolved organic matter with the polymer. Exposures of polymeric passive sampling devices in agitated sediment slurries have shown that exchange kinetics can be increased substantially when compared with exposures in water [131]. Exposures in static conditions are more complex to interpret[131]. Contaminant exchange kinetics for polymer exposures in sediment will also depend on sediment-based parameters such as porosity or dissolved and particulate organic carbon content.

3.3.1 Migration within the polymer matrix

The ability of chemicals to move within the plastic matrix will depend on the physico-chemical properties of the chemical additive and of the polymeric matrix (Table 9). Polymers can be glassy or rubbery depending on whether their glass transition temperature (T_g) is above or below ambient temperature. Glassy polymers exhibit a significant proportion of condensed regions in the polymer while rubbery polymer will present less structured and more flexible amorphous (non-crystalline) polymer regions. Polymers such as LDPE can present rubbery polymer regions as well as more crystalline parts of the polymer with characteristics midway between rubbery and glassy polymer characteristics. Differences in proportions of these different regions will affect the rate of diffusion of chemicals within the plastic and the capacity of the polymer to absorb chemicals. Absorption of chemicals generally takes place in the

amorphous regions of the polymers. For example, rubbery polymers such as low-density polyethylene (LDPE) and silicone have T_g values of -68 and -127 °C. LDPE presents a majority of amorphous regions and some crystalline polymer sections. Polyvinylchloride (PVC) on the other hand is a glassy polymer at ambient temperature since it has a T_g of 80 °C. The proportion of glassy and rubbery regions in a polymer will have an impact on the ability and rate at which chemicals diffuse within the polymer matrix.
Lower contaminant diffusion coefficients have generally been measured in glassy polymers than in rubbery ones. In a review of transport of chemicals within polymers, George et al.[132] showed that benzene diffusion coefficients in various polymers generally decreased with increasing T_g[132]. Higher diffusion coefficients of polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) have been measured in silicone rubber than in low density polyethylene [133]. Fries et al. [134] demonstrated lower diffusion coefficients for selected PAHs in high-density polyethylene (HDPE) than in LDPE. This is not surprising since HDPE will present substantially more crystalline regions than LDPE that will contribute to reduce contaminant diffusivities. Similarly, Teuten et al.[115] reported contaminant diffusion coefficients in HDPE three to four orders of magnitude higher than in PVC. The diffusion coefficients for dimethyl and dibutyl tin stabilizers in PVC (PVC pipes) was estimated to be in the range of 2.0 10^{-17} to 2.0 10^{-18} m^2/s [135]. While the size of the penetrant has generally been expected to be the main chemical-related parameter influencing the transport of chemicals in polymers, other factors such as the shape of the diffusing molecule, its minimum cross section, flexibility or possible interaction with the polymer matrix are likely to play a major role in the diffusion of chemicals through polymers. Reynier et al.[136] used a film-stacking experiment to examine the effect of size and shape parameters on the diffusivity in polypropylene of plastic additives such as antioxidants relevant to the foodstuff industry. Both size and shape influence the diffusivity and the authors attempted to further understand the effect of the mode of displacement of flexible and more rigid molecules within the matrix.

3.3.2 Sorption capacity of polymeric microparticles

The type of polymer and its state (i.e. glassy or rubbery) will also influence how sorption of additives and organic contaminants takes place. Different sorption mechanisms have been observed for different polymers. Linear sorption isotherms (when the concentration in plastic is constantly proportional to the concentration in water across a wide range of concentrations) are generally the result of absorption to rubbery polymer regions while non-linear sorption isotherms (when the concentration in the plastic deviates from linearity when under specific water concentration levels) have been explained by adsorption processes to glassy regions described by Freundlich and Langmuir models. The type of sorption will affect the extent of sorption and polymer-water desorption rates. Since sorption to glassy polymers is a surface process, the number of adsorption sites may be limited and this can give rise to competitive sorption of different chemicals onto microplastic particles made of glassy polymers[60].

The sorption capacity of polymers is generally high for hydrophobic and non-ionised chemicals. Polyethylene-water partition coefficients (K_{Pew}) for polycyclic aromatic hydrocarbons, polychlorinated biphenyls and other chlorinated compounds in the range 10^3-10^8 L/kg have been reported on many occasions[130,137–139]. This means these compounds are effectively absorbed by such polymers. Most of these measurements have been undertaken using milliQ water at ambient/laboratory temperature. Lower temperature and increased salinity (salting-out effect) will tend to reduce the solubility of chemicals in water and increase apparent polymer-water distribution coefficients[140]. Lee at al.[141] evaluated the sorption of selected PAHs and chlorinated compounds from seawater to three types of laboratory-generated microparticles of polyethylene, polypropylene and polystyrene. Distribution coefficients were in the range of the compound's respective K_{ow}.

More attention recently has been given to assessing the sorption of chemicals to polymers at the microscale. Teuten et al.[125] reported the measurement of polymer-seawater sorption isotherms for phenanthrene adhesion to sub-millimetre particles of polyethylene, polypropylene and polyvinyl chloride. They showed that phenanthrene sorption was highest to the LDPE and lowest for the PVC. Another study of the sorption of phenanthrene to millimetre-size pellets of PE, PP and POM this time reported highest distribution coefficients for PE[142]. Distribution of phenanthrene between water and eroded plastic pellets (of unknown polymer type) were similar to those measured for the plastic pellets. Distribution coefficients determined in seawater were slightly but not significantly higher than those found in artificial freshwater[142]. More recently Rochman et al.[143] studied the sorption of hydrophobic contaminants to pre-production pellets representative of five types of plastics deployed in a marine environment under urban pressure for pellet exposure durations up to 12 months. The sorption of PAHs and PCBs was highest for LDPE and HDPE and lowest for PVC and PET. This study supports previously obtained data demonstrating higher plastic-water distribution coefficients for PE (related to the absorptive capacity of PE) compared with PVC or PP. This work is also the first to assess hydrophobic contaminant sorption to PET. Furthermore, contaminant accumulation curves over a one year period were generally in agreement with passive sampling theory[144,145]. In other words, PE concentrations of the least hydrophobic PAHs and PCBs were seen to plateau during exposure, as a result of reaching equilibrium with the freely dissolved concentration. Accumulation curves showed that equilibrium was not reached for the more hydrophobic contaminants[143]. Velzeboer et al.[146] studies the sorption of PCBs to micrometer-size PE and nano-size PS. Sorption isotherms for PE were linear and of a similar order of magnitude to that of sediment organic matter and indicative of partitioning-based sorption. Sorption to nano-sized PS was significantly stronger (as a result of aromaticity and the surface-to-volume ratio of the PS particles compared with PE) than to micro-sized PE and isotherms for PS were non-linear. The presence of (dissolved) organic matter appeared to affect the sorption of PCBs to nano-sized PS. DOM sorption to the surface of PS can reduce the availability of sorption sites and reduced overall apparent distribution coefficients. The presence of salt in water increased polymer-water distribution coefficients of PCBs for nano-sized PS and micro-sized PE.

Endo et al.[147] studied the dissipation of PCBs from field-collected PE pellets. The fraction of PCBs remaining in the pellets at the end of the 128 day experiment increased with increasing PCB hydrophobicity. An aqueous boundary layer controlled uptake model was able to reproduce the PCB dissipation curves with dissipation half-lives in the range of 14 days to 210 years. Choi et al.[148] investigated the release into water of brominated flame retardants (additives) from original millimetre-size high impact polystyrene pellets in which decabromo diphenyl ether was present in highest concentrations. Higher flame retardant concentrations in solution where obtained when using water containing humic acid at a concentration of 1 g L^{-1} organic carbon. This DOC may have had the effect of increasing the solubility of these very hydrophobic chemicals in water and the mass transfer through the aqueous boundary layer at the surface of the sampler.

One subject that has received less attention is the sorption of trace metals to microplastic. Interaction of metals with plastic storage containers has been identified as a possible artefact in the analysis of trace metals in water[149,150]. Ashton et al.[151] measured a range of trace metals associated with beached plastic pellets. Adsorption of metals from water to new polyethylene pellets exposed to harbour water for 8 weeks was also shown. A more recent study by Holmes et al.[152] aimed to evaluate trace metal adsorption kinetics and sorption isotherms for new and beached polyethylene pellets. Both Langmuir and Freundlich models fitted the data and the adsorption of trace metals was found to be higher for littered pellets than for new ones.

3.4 Biota-plastic transfer of contaminants

Plastic additives and contaminants sorbed during exposure of microplastic particles in the environment can ultimately be transferred into organisms upon ingestion, contact or inhalation. With the worldwide occurrence of microplastic particles in the marine environment, this theme has received increased attention in recent years. If a contaminant concentration gradient between the organism and the ingested plastic exist, gut fluids have the potential to facilitate the transport of chemicals from the plastic to the organism. While laboratory studies have demonstrated that transfer of chemicals from ingested plastic particles to the organism is possible, whether the magnitude of this process is sufficient high to influence bioaccumulation and magnification of these chemicals into organisms and food chains is not certain. So far, plastic-sorbed contaminant transfer into organisms does not appear to be very significant. More work in the laboratory and in the field is needed to confirm this.

Studies in the late 1980s already highlighted the possibility of plastic ingestion as a mode of transfer of contaminants into marine organisms [129]. Most marine organisms whether they live in the water column or in the sediment are likely to be exposed to microplastics through ingestion (See chapter 2.2). Guts of organisms may provide a suitable environment for increased leaching of microplastic-sorbed contaminants. The presence of organic matter and fluids with surfactant-like properties in gut fluid can contribute to solubilizing hydrophobic contaminants and reduce the sediment or polymer-water mass transfer resistance[154,155]. Recent work showed that simulated gut fluid conditions and temperature could substantially increase the desorption of contaminants such as phenanthrene or DDT from microplastic particles[156].

Multimedia and food-web modelling studies suggested that when adding a polyethylene phase in the environment, over 1 % of hydrophobic substances (with $\log K_{ow} > 5$) may partition to polyethylene, but that microplastic may remain a minor route of uptake into organisms for persistent organic pollutants[48]. Teuten et al[125] on the other hand predicted that a concentration of 1 μg of contaminated PE per gram of sediment could result in an increase in equilibrium concentrations of phenanthrene in the lugworm *Arenicola marina*. Addition of clean plastic to sediments was expected to decrease equilibrium concentrations in *A. marina* since the polyethylene would be providing an additional[157] sink for the chemical in the sediment-biota system. These researchers indicated a need for more knowledge regarding gut retention time (GRT) and kinetics of transfer of contaminants to/from microplastic during gut passage.

Also using the lugworm *A. marina* as test species, Besseling et al.[157] evaluated the effects of the presence at different concentrations of polystyrene microplastic pellets on the health and PCB bioaccumulation in these organisms. Increased microparticle uptake and weight loss was observed with increasing microparticle content of the sediment. The lowest microplastic dose resulted in a moderate increase in PCB bioaccumulation, an increase which was less significant for the two higher microparticle doses. Since microparticle contents tested in this study (0.074-7.4 % dry weight) were higher than those encountered so far in sediments, the authors concluded that the effect of PS particles on the transfer of PCBs to the lugworm was small. The incorporation of plastic ingestion in a biodynamic model of POP bioaccumulation in sediment showed that the presence of polystyrene particles would result in minor decrease in bioaccumulation in *A marina*[26]. Scenario runs with more strongly sorbing polymeric microparticles such as PE showed that cleaning and dilution mechanisms would tend to decrease bioaccumulation in the lugworm. All in all, the microparticle concentrations generally found in sediments globally are much lower than those evaluated here. This means that the effects described here are not likely to be significant for the risk assessment of plastic on the bioaccumulation of POPs in the lugworm. While such a conclusion is plausible for POPs present in sediments in general, the situation may be different for chemical additives possibly present in the microplastic. Further modelling work showed that the microplastic is not likely to be a very relevant pathway for the bioaccumulation of the chemical additives bisphenol A (BPA) and nonylphenol[59]. Browne et al.[25] demonstrated that organic substances such as nonyphenol, phenanthrene, triclosan or PBDE47 were able to transfer from PVC microparticles to the lugworm *A. marina*. Uptake of nonyphenol and triclosan from the microplastic resulted in a decrease in the capacity of the lugworm to remove pathogenic bacteria and to burrow, respectively. Sampling and modelling microplastic contamination along a transect in the Southern Atlantic Ocean in relation to contaminant concentrations measured in mesopelagic lanternfish, Rochman et al.[158] observed that fish from sampling stations with higher plastic concentrations exhibiting higher concentrations of higher brominated diphenyl ether congeners (sum of BDE183, 197 and 209). The authors propose these compounds may be indicators of plastic contamination of the marine environment, linking the presence of plastic with the accumulation of these chemicals in biota. In another field study, Tanaka et al [159] looked at PBDE congener profiles in paired adipose tissue-stomach plastic for *Puffinus tenuirostris* sampled in North Pacific Ocean. Data from three birds that showed the presence of highly brominated congeners both in the bird's adipose tissue and in the plastic suggest that plastic ingestion may be responsible for the concentration of BDE209 observed in these birds. Chua et al.[160] evaluated the effect of micro-size PE particles obtained from exfoliating face scrub soap on the bioaccumulation of PBDEs in the marine amphipod *Allorchestes compressa*. When PBDEs were added to seawater containing microplastic and the amphipod, the microparticles acted as an additional sorption phase in the system, resulting in an overall reduction of bioaccumulated PBDEs when compared with a seawater-only treatment. PBDE uptake by the amphipod appeared to be PBDE concentration-dependent, since the proportion of bioaccumulated PBDEs was lower for the higher concentration level. When PBDE were sorbed to the PE particle prior to amphipod exposure to these particles, the proportion of PBDE added to the system and that was assimilated by the amphipod was slightly lower than when the contaminants were added directly to the test system.

4. Effects of microplastics on marine biota

4.1 General

With around 88% of the ocean's surface contaminated with microplastic[8] a large number of marine species come in contact with microplastics[9]. It is clear that marine organisms ingest microplastics (Section 2.2; Table 6) and that laboratory experiments show that this can result in harm (Table 10). Microplastics ingestion in situ has been documented for the Norway lobster, *Nephrops norvegicus* [93] and could also be simulated under laboratory-controlled conditions. In contrast, no egestion of fibers was recorded, indicating that microplastics may remain long-term, if not permanently, inside the animals once ingested. The fibers found probably originate from fisheries-related gear. The effects of microplastics on marine organisms are typically sub-lethal, such as reduced feeding[161,162] and increased uptake of certain contaminants (e.g. PCBs)[157]. In addition to sub-lethal effects, it is also been suggested that microfibers can block the digestive tract[9]. A recent study has shown that microplastic particles can induce hepatic stress in fish and demonstrated a more pronounced effect for the combination of microplastic and associated contaminants[163]. These authors further suggested that microplastics are an exposure pathway for hydrophobic organic contaminant uptake into fish. Browne et al.[25] demonstrated that organic substances such as nonyphenol, phenanthrene, triclosan or PBDE47 were able to transfer from PVC microparticles to the lugworm *A. marina*. Furthermore, PVC on its own made the lugworm more susceptible to oxidative stress. Uptake of nonyphenol and triclosan from the microplastic resulted in a decrease in the capacity of the lugworm to remove pathogenic bacteria and to burrow, respectively. Rochman et al.[158] observed changes in gene expression that may be influenced by the estrogen receptor alpha, vitellogenin I and choriogenin H in adult Japanese Medaka following one or two month exposures to millimetre-size pre-production polyethylene pellets. Effects were observed with both virgin pellets and pellets exposed in the marine environment for three months. For further details about the link between POPs and microplastics, see chapter 3.

All studies to current date on microplastc in marine biota have been performed with a cut off at the micrometer scale (Table 10). We know that plastics are broken down into smaller and smaller pieces, and that it highly likely that nanoparticulate plastics are present in the ocean, although this has yet to be quantified. Nanoparticulate plastics possibly pose the greatest threat to marine organisms and it has been shown that freshwater water flea (*Dapnia magna)* exposed to nanoplastics affected reproduction[164]. An interesting observation is that 10 nm polystyrene particles increased in bioavailability to blue mussels when present in aggregates of 2 μm suggesting that size has an important role to play on the toxicity of nano- and microplastics[165]. As micro- (and nano-) plastics are ingested or otherwise adhere to organisms at different trophic levels, it is clear that there is considerable potential for bioaccumulation and trophic transfer of microplastics in food chains, such that higher predators, including human consumers of seafood products, may possibly be exposed to relatively high levels of microplastics

Table 10. Examples of effects from microplastic exposure in the laboratory.

Organism	**Species**	**Polymer**	**Size (µM)**	**Concentrations**	**Duration**	**Ingestion (Y/N/NA)**	**Effect (L/S-L/N/NA**	**Reference**
Sea urchin (larva)	*T. gratilla*	PE (fluorescent)	10-40	1,10,100 and 300 particles/mL	5 days	Y	N	166
Polychaetes	*A. marina*	PVC (unplasticized)	Dust	0 - 5% sediment weight	4 weeks	Y	S-L	161
Polychaetes	*A. marina*	PS (fluorescent) (-/+ PCB in sediment)	400-1,300	0 - 7.4% sediment weight	28 days	Y	S-L	157
Blue mussel	*M. edulis*	PS (fluorescent)	3 and 9.6	15,000 individual spheres	3h and 2 h exposure	Y	S-L	167
Barnacles Lugworms	*S. balanoides* *A. marina*	Natural occuring microplastics	NA	1g/L 1.5g/L	NA	Y	NA	30
Shore crab	*C. maenas*	Polystyrene (fluorescent)	8 - 10	$4.0 \times 10_3$ microspheres/·L	24 hours 21 days	Y	NA	91
Blue mussel	*M. edulis*	High-density polyethylene (HD-PE)	0–80 µm	2.5 g HDPE-fluff	96 hours	Y	S-L	162

Y: yes, N: no, NA: no data
L: Lethal, S-L: Sub-lethal

4.2 Plankton

There are to date no reports on adverse effects of microplastics on photosynthetic phytoplankton. These microalgae fix carbon from inorganic CO^2 and energy from sunlight and as such have no need for uptake of particulate organic matter. Thus, health issues relating to ingestion of microplastics are unlikely. Indirect toxicity effects may be expected from hazardous chemicals leached into the habitat by microplastics, if colocating with microalgae in high abundance. Nanoplastics, in contrast, are small enough to penetrate cell walls and membranes and have been shown to reduce population growth and chlorophyll concentrations in the green alga *Scenedesmus obliquus*[164]. Many protozoans are, however, mixotrophic and can choose between photosynthesis and heterotrophic feeding modes. For heterotrophic protozoans, such as ciliates, microplastics uptake through phagocytosis has indeed been shown in experimental studies where polystyrene beads have been used to quantify feeding rates and preferences[18,168]. Cole et al.[51] also recorded ingestion of microbeads of 7.3 µm size in the dinoflagellate *Oxyrrhis marina*.

Similar studies are available for zooplankton, especially copepods[169,170]. A more recent paper has systematically examined the ingestion of microplastics (7.3-30.6 µm) in 15 different zooplankton taxa ranging from copepods to jellyfish[51]. Thirteen (87%) of the fifteen taxa tested showed ingestion. The only exceptions were siphonophores and chaetognaths, while some copepods (*Acartia claus*i) and decapod larvae showed ingestion of some sizes but not others. Another study with species from the Baltic Sea showed microplastics ingestion for mysid shrimps, copepods, cladocerans, rotifers, polychaete larvae and ciliates[171]. The highest proportion of individuals with microplastics ingestion was found for pelagic polychaete larvae of the genus *Marenzelleria*. Microplastics are egested again by copepods and mysids in fecal pellets[171]. This fecal material is then available to other organisms, both in the water column and in the benthos as fecal materials sinks out of the water column to the seafloor. Hence, microplastics repackaged into dense and nutritious fecal pellets may provide another exposure route of microplastics to other food chain compartments and at the same time increase their vertical transport as part of the biological pump. Microplastics were ingested at the expense of algal ingestion, as shown by a negative relationship between algal ingestion rate and microplastic concentration in the copepod *Centropages typicus*[51] and may also shift the size preferences of filter feeders towards size ranges that differ from the particle size of the plastics as an avoidance strategy [172]. If such shifts include a shift to less nutritious food items and/or an energetically more costly feeding mode, the energy balance of the feeding organism will be negatively affected, with potential knock-on effects on growth, reproduction and fitness. Increased mortality rates and reduced offspring viability were observed in a common copepod of the NE Atlantic, *Calanus helgolandicus*, when exposed to high concentrations of microplastics, and a significant metabolic cost was estimated and attributed to reduced ingestion of nutritious food [173]. Coherent anti-Stokes Raman scattering (CARS) microscopy showed that microplastics adhere to various external and internal body parts of copepods, including the alimentary canal, furca and urosome, as well as swimming legs[51]. External mass accumulation of microplastics in fine hairs and spines of feeding and swimming appendages may have a number of adverse effects that are yet unstudied, including locomotion and escape response, creating a feeding current to attract food, mate finding and copulation and egg hatching in egg-carrying species. Translocation of microplastics between tissues has so far not been reported for zooplankton. Nanoplastics have reportedly toxic effects on meroplanktonic larvae of sea urchins depending on their surface charge and aggregation state[174]. Nano-polystyrene amine (PS-NH_2) induced strong developmental defects and malformations in echinoderm embryos of the species *Paracentrotus lividus*, with EC_{50} at 3.85 μg mL^{-1} (24 h post-fertilisation) and EC_{50} 2.61 μg mL^{-1} (48 h post-fertilisation).

4.3 Benthic organisms

Sediments are a sink for microplastics with the benthic community a very important component of marine ecosystems, accounting for as much as 98% of all marine organisms[175] and as such oysters, blue mussels, barnacles and lobsters have all been shown to ingest microplastics (discussed in 2.2). In addition, it has also been demonstrated that other benthic species, such as sea urchins and polychaetes ingest microplastics under laboratory conditions (Table 10). Sea urchin larvae, under experimental conditions, have been shown to ingest microplastic particles in size range of 10 – 40 μM, which are a similar size to their natural prey (Table 10). Ingestion increased with the increased concentration of microplastics, however exposure to particle concentrations an order of magnitude higher than the highest measured environmental concentration, which was recorded in the Baltic Sea, did not result in any measureable harm[166].

The benthic worm *Arenicola marina* is of high importance for the marine food webs due to its high lipid content[161]. *A. marina* ingests large amounts of sediment and subsequently will ingest microplastic particles at the same time as feeding. Several studies have looked at microplastic impact on *A. marina* with a long term chronic exposure to environmental realistic levels of polystyrene (400-1300 μM) causing a dose dependent reduction in feeding capacity followed by a dose dependent reduction in weight[157]. In addition to polystyrene and natural occurring microplastics[30], *A. marina* have also been shown to ingest PVC dust[161] which over a 4 week period of exposure to 0 - 5% PVC dust, caused a significant decrease in lipid content. Some of these findings are worrying for this marine worm when considering all the plastic waste we know is lying on the sea floor[81].

Wild mussels have been shown to contain microplastics (Table 6) and several laboratory studies have investigated the effects of microplastic exposure to mussels (Table 10). The translocation of microplastics from the digestive system into the circulation system has been reported, which remained 48 days following exposure[157,162,167]. This is of importance since mussels are such an important food source for humans, and if the plastics are translocated into the circulation system, it will actually been taken up in the mussel and will stay there for a long time. Also other studies have shown that microplastics can accumulate in the tissue of the blue mussel (particles from 0-80 μM) (Table 5)[162].

Shore crabs have been shown to ingest via the gills and also through eating blue mussels pre exposed to microplastics[91]. Microplastics taken-up across the gills were retained for a longer time (21 days) than when taken up via food (14 days). This can indicate that different uptake pathways can affect the impact of microplastics on organisms making organism with gills more vulnerable than by ingestion.

4.4 Fish

Fish, as discussed in section 2.2, are known to ingest microplastic particles in the wild. Few studies have to date investigated the effects of microplastic exposure to fish. But one recent long-term study of Japanese medaka (*Oryzias latipes*) showed early warnings signs (effects on genes associated with reproduction) when exposed to environmental realistic concentrations (8 ngL^{-1}) of virgin polyethylene and polyethylene (size <0.5 mm) weathered in the sea (San Diego Bay, CA) and possibly containing POPs ([158]; Table 10). This study shows that environmental realistic doses of microplastics can affect fish in a sub-lethally way, and that weathered microplastics are more harmful than virgin microplastics.

The digestive system of wild caught fish typically contains between 1 and 7.2 particles and this possibly illustrates that the microplastics passing straight through the fish and do not block the digestive system or bioaccumulate. A fish that accumulates plastics in their gut may become malnourished and starve, with a resulting worse-case scenario of decreased fish populations[50]. Although, it has been seen that larger fish typically contain more plastic pieces in the gut than smaller fish, it is not known if these particles have been recently consumed or accumulated over time[50]. Knowledge is needed on fish gut retention to determine this, which subsequently makes it a topic of high importance for further study[50]. Further knowledge is required as to whether plastics can pass through the gut wall and enter the flesh of the fish. No studies have yet demonstrated translocation of microplastic across the fish gut, which poses a potential risk for human food safety[9] .

4.5 Seabirds

That plastic litter is a hazard for seabirds has been known for several decades, with the first records dating back to the 1960s and 70s, while widely used standardized sampling protocols are much more recent [176,177]. Some seabirds seem particularly susceptible to the ingestion of micro-, meso- and macroplastics, while plastic ingestion is negligible in other species[178]. Birds feeding on the sea surface, such as the northern fulmar, the albatross, shearwaters and petrels, are especially exposed, but plastics have also been recorded in diving species[178], such as the puffin, and many species have not been studied at all [176].

In the 1990s almost 30% of the plastics found in seabirds were industrial pellets[178]. More recently this seems to have shifted to a larger proportion of consumer plastics[99], which may indicate either better prevention of plastic pellets entering the environment or a general proportional increase of consumer plastic waste ending up in the sea. A regional comparison in the same study on the northern fulmar showed a latitudinal gradient of plastic contamination from the North Sea to the Faroe Islands and the Arctic. This pattern has, however, recently been refuted as new data from Svalbard in the European Arctic show much higher plastic levels in northern fulmars than expected[179] and have similar contamination levels as birds from industrialized areas further south. Plastic particles may be eaten intentionally or ingested secondarily when hidden within a food item[180]. Plastic ingestion not only poses a health risk relating to feeding inhibition and subsequent starvation, but also exposes seabirds to contaminants associated with plastics[153,159,181] and may negatively impact on the birds' fitness.

4.6 Large marine animals such as marine mammals and turtles

Many large marine organisms have been shown to be highly impacted by plastic litter. Mesolitter has been documented to lethally harm marine mammals due to ingestion and entanglement[6]. For example, sea turtles are known to be directly hurt by plastic waste in the ocean with one example in Brasil that showed 60.5% of the turtles had marine debris in their digestive system, whereby most of this was plastic[182]. There are also numerous reports of stranded whales or other marine mammals found dead having a lot of man-made substances in their gut, often plastics. This plastic litter is often not defined in size, polymer type, origin or scientific studied, with small sample sizes as typically only individuals, are collected, however these reports indicate that marine mammals are highly impacted by plastic contamination in the ocean. Moreover, it would not be ethical to capture a sufficiently high number of large marine mammals to get a sufficiently large data set to statistically confirm this[31]. Many whale species, for example the Baleen whale, are filtering organisms that efficiently filter seawater which makes them highly vulnerable for microplastic ingestion[53]. With a long lifespan and high fat content, there is the potential for whales to accumulate POPs[183] but also to ingest and accumulation microplastics. Although to our knowledge no studies have been performed on Polar bears, they are already known to be vulnerable to many of the hazardous chemicals associated with plastics. They are known to contain high concentration of harmful organic contaminants, for example brominated flame retardants found in some plastic materials[184]. Also if plastic bioaccumulate (Section 5.7) they may be exposed to microplastics from their prey, as for example the ringed seal which is their primary food source.

4.7 Transfer of microplastics in the food web

Little is known about whether microplastics can transfer up the food web and represents an important knowledge gap. Only two studies have so far demonstrated that microplastics can be transferred from prey to predators. Farell et al.[185] found microplastics previously ingested by the blue mussels in the haemolymph, stomach, hepatopancreas, ovary and gills of the crab *Carcinus maenas*. When mysids were offered to zooplankton as food that had previously ingested polystyrene beads, the microplastics were observed in the intestines of the mysids within 3 h of exposure[171] . More information on the impacts of plastic transfer and possible accumulation in the food web is needed

5. Conclusions and recommendations

5.1 Conclusions

- Microplastics contaminate the marine environment globally. They are found in the water column, sediments and marine organisms.

- The source of these microplastics is the direct release of microplastic particles, primarily used in personal care products and plastic manufacturing as well as the breakdown of larger plastic objects and the shedding of fibres from synthetic materials.

- The proportions of samples containing microplastics ranges widely, but most studies have found microplastics in the majority of the samples collected (i.e. > 60%).

- High concentrations of microplastics have been found at five oceanic gyres (North Atlantic, South Atlantic, South Indian, North Pacific and South Pacific), and in addition predict a hitherto unreported patch in the Barents Sea.

- Buoyancy is a key parameter when considering the fate of microplastics.

- Concentrations of microplastics in the water column range from less than 1 to several hundred particles m^{-3}, but measurements are inconsistent in terms of both sampling methods (device, mesh size and depth layer(s)) and units measured, highlighting the need for scientific conventions and standardizations with respect to sampling and quantification of pelagic microplastics.

- There is a 100-fold difference between measured and predicted loads of plastics in the ocean as well highlighting an important gap in the size distribution of floating plastic debris. It has been hypothesised that there is substantial loss of plastic from the ocean surface, most likely due to the fast breakdown of plastic fragments from millimeter to micrometer the preferential submersion of small-sized plastic with high surface:volume ratio and reduced buoyancy due to biofouling, ingestion by marine organisms and subsequent defecation as well as yet unidentified processes.

- Much of the debris found on sediment is plastic (up to 96%) with sediments and beaches a sink for microplastics. As many as 120 particles L^{-1} sediment have been reported. Synthetic fibers are often the dominant type of microplastics found in the water column and sediments.

- Organisms are known to ingest microplastic particles, including many commercially important marine species.

- Ingestion of microplastics is well known and the digestive system is often examined when looking for the presence of microplastic. Exposure via the gills has not been demonstrated in the environment, but several suspension-feeding organisms have been reported to contain microplastics and this might be due to uptake over the gills.

- Plastic contains additives, chemicals added to improve the desirable properties of the plastic product. Many of these additives are known hazardous substances and can leach from the plastic surface. While only a limited number of classes of chemicals (e.g. POPs) have been assessed in plastic particles until now, plastics are likely to be able to sorb a wide range of chemicals.

- Chemical additives present in microplastics have the potential to be released upon discharge of these polymeric particles into the marine environment. Molecular size is a key property of the additive when evaluating how fast it migrates through and out of the plastic. The smaller the additives, the faster the migration.

- The following factors influence the transfer of organic contaminants from and to microplastic particles; concentration gradient, sorption process, contaminant characteristics, type of polymer, size and conformation of microplastic particles, polymer degradation and erosion, biofouling, water turbulences and boundary layer, temperature and salinity, ingestion and sediments.

- Plastics have the potential to act as vectors for the transport and release of contaminants and additives. Plastic-based fluxes of contaminants to the Arctic have been estimated to be relatively minor in comparison with atmospheric and oceanic currents.

- Contaminant concentrations on plastic debris and particles sampled from beaches may be representative of concentrations in their surroundings. Particles from heavily polluted areas contain higher levels than those from less polluted areas.

- Laboratory experiments have demonstrated that plastic-sorbed chemicals can transfer into organism upon ingestion. At environmental levels, it is not clear yet whether the ingestion of plastic with sorbed contaminants and additives by marine organisms will affects bioaccumulation of these substances.

- It is clear that marine organisms ingest microplastics and that laboratory experiments show that this can result in harm.

- There are no documented reports of direct effects of microplastic ingestion on wild organisms. The effects of microplastics on marine organisms are typically sub-lethal, such as reduced feeding and increased uptake of certain contaminants (e.g. polychlorinatedbiphenyls). Laboratory exposure to microplastics shows negative impact such as a reduction in the growth of marine worms and changes in gene regulation in fish.

- There is a lack of data on the levels of microplastics present in the Norwegian environment.

- The levels of anthropogenic particles (10–500 µm) in the Skagerrak seem lower than those found in the Baltic, however these data are not conclusive.

- Northern fulmars (*Fulmarus glacialis*) are consuming plastics. Recent findings suggest that 95% of northern fulmars in the North Sea had plastic in their stomachs and that 58% contained levels above the 0.1g identified as an OSPAR Commission environmental quality objective. With respect to the Norwegian coast and specifically the Skagerrak, 50% of investigated northern fulmars contained levels above 0.1g.

- With the evidence available it is not possible at present to draw any sound conclusions on the direct risks posed by the occurrence of microplastic particles in the marine environment or the influence of microplastics on the risks posed to environmental and human health when associated with hazardous substances such as additives and POPs.

5.2 Recommendations

Recommendations are broken down into a number of key areas:

1. Standardization

There is an urgent need for the standardization of approaches for the quantitative determination of microplastic pollution. This ranges from the simple definition of a microplastic to how data are reported. Such standardization is essential for the comparison of data and the evaluation of spatial and temporal trends.

2. Monitoring

There is an urgent need to evaluate the extent of microplastic pollution around the coast of Norway and Svalbard, including the direct inputs from marine discharges, such as treated wastewater. Long-term monitoring is required to monitor the load of microplastics in the Norwegian marine environment.

3. Fate of microplastic in the marine environment

We need to know more about what happens to plastic in the ocean. There is a need to identify the main processes that affect microplastic fate and how these processes in fact affect plastics.

4. Direct effects of microplastic

Further studies on the effects of microplastics on marine organisms are required. Understanding whether microplastics can move up the food chain is a key question.

5. Influence of hazardous substances and additives on the effects of microplastic

Studies are required on understanding how additives and POPs in plastic influence toxicity and bioaccumulation/biomagnification.

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Gaustadalléen 21 • NO-0349 Oslo, Norway
Telephone: +47 22 18 51 00 • Fax: 22 18 52 00
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