Microplastics and Nanoplastics

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Understanding microplastic pollution in the Nordic marine environment – knowledge gaps and suggested approaches

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Abstract

This paper examines a number of specific, practical recommendations to advance knowledge and move towards evidence-based solutions to microplastic (MP) pollution in the Nordic marine environment. The paper approaches the subject of MPs holistically, emphasises the knowledge gaps and challenges in answering pressing questions, discusses the limitations that so far have prevented these questions from being solved, and suggests approaches for answering them. The Nordic context is chosen due to the global importance of its ecosystem that is threatened by MP pollution, exacerbated by climate change. The research questions discussed pick up knowledge gaps identified in attempts to answer the most pressing questions of our time regarding marine MP pollution and are applicable to some or all seas of the Nordic region, from the Baltic and North Seas in the south to the Arctic in the north.

The research questions relate to sources, sinks and transport of MPs, and how food webs are potentially impacted in Nordic marine environments. In addition, we point out the relevance for stakeholders expected to use the emerging knowledge. Through this exercise, using concrete examples, we aim to invite discussions on how a concerted effort by the Nordic countries can bring MP research to a higher level of understanding needed to address the MP pollution problem in Nordic marine habitats.

Keywords: Impact, Plastics, Plastic chemicals, Transport, Toxicology

Introduction

In line with increasing global plastic production, plastic waste emissions have also increased substantially [21]. These include microparticles < 5 mm [43], mostly from degradation of larger plastic litter. Microplastic (MP) research has expanded rapidly in recent years, including studies on the occurrence and possible impacts of MPs in the Nordic countries and the Arctic [111, 73, 159]. MPs have been found in all parts of the Nordic marine environment from sea ice, sea water, coastal sediments and beaches to deep-sea sediments, as well as ingested by invertebrates and seabirds [142, 154, 17, 53, 103, 107, 65, 186]. As plastics often include additives, individual monomers, and other associated chemicals [72, 55], the widespread occurrence of MPs may also introduce undesirable chemicals to the marine environment.

In this paper, we have assembled some unanswered research questions relevant for the Nordic marine environment and defined as key to the progression of the scientific field. The research questions are a result of a workshop in the NordMar Plastic network (https://nordmarplastic.com) where attending experts from the Nordic countries were asked to put forward relevant questions in their respective field of expertise and to provide argumentation for why the questions

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are important, what the current state of knowledge is, how the questions could be addressed and who would be interested in the results. The questions were subsequently grouped (Table 2) as relating to "Sources, sinks and transport" and "Exposure and potential impacts".

The motivation for and objective of this paper was thus to identify knowledge gaps for MPs in the Nordic region, explain their significance and provide suggestions how to address them.

These suggestions include conceptual and practical considerations, experimental and modelling approaches, as well as field surveys and monitoring. Current challenges in reaching a higher level of understanding of MPs in the Nordic marine environment are identified, and recommendations to overcome existing obstacles presented. The focus is on the marine environment of the Nordic ecoregions from the Baltic Sea and North Seas in the south to the Barents Sea and the Arctic Ocean in the north. Features that are unique to the regions are highlighted and pinpoint the challenge(s) for the selected research questions in the specific ecoregion.

The Nordic marine environment

The Nordic marine environment comprises the seas surrounding the Nordic countries (Fig. 1), including the Norwegian Sea, Greenland Sea, the Norwegian, Swedish and Danish sectors of the North Sea, as well as the Baltic Sea. It also includes the Arctic Ocean, Barents Sea, Icelandic waters and North-East Atlantic Ocean (Fig. 1).

The Baltic Sea (Table 1) is a brackish semi-enclosed shallow sea with many islands and a diverse coastline [115]. The input from the surrounding nine countries has resulted in that the Baltic Sea is one of the world's most impacted seas regarding chemical pollution [44, 99, 78]. For MP emissions to the Baltic Sea, urban sewage water pathways are important [165]. Model calculations of emissions of polypropylene (PP), polyethylene (PE) and polyethylene terephthalate (PET) MP particles from land-based sources in the Baltic Sea indicate that in semi- or enclosed water bodies, such as bays and lagoons, the highest MP accumulations are found on the shores. These systems function as sinks for MPs and thus protect the open Baltic Sea from MP pollution. Most MPs are therefore not transported over long distances but are washed ashore soon after their emission [166].

The Baltic Sea is connected to the North Sea via the Danish straits and Öresund (Table 1) and the Baltic Sea current transports pollution into the North Sea. The North Sea is a shallow sea, encompassing the unique ecosystem of the Wadden Sea [46, 90]. It is surrounded by one of the most industrialised areas of the world with large rivers like Elbe, Thames and Rhine/Meuse discharging into the sea [146, 155, 133]. Results of MP quantification in the River Elbe show higher abundance

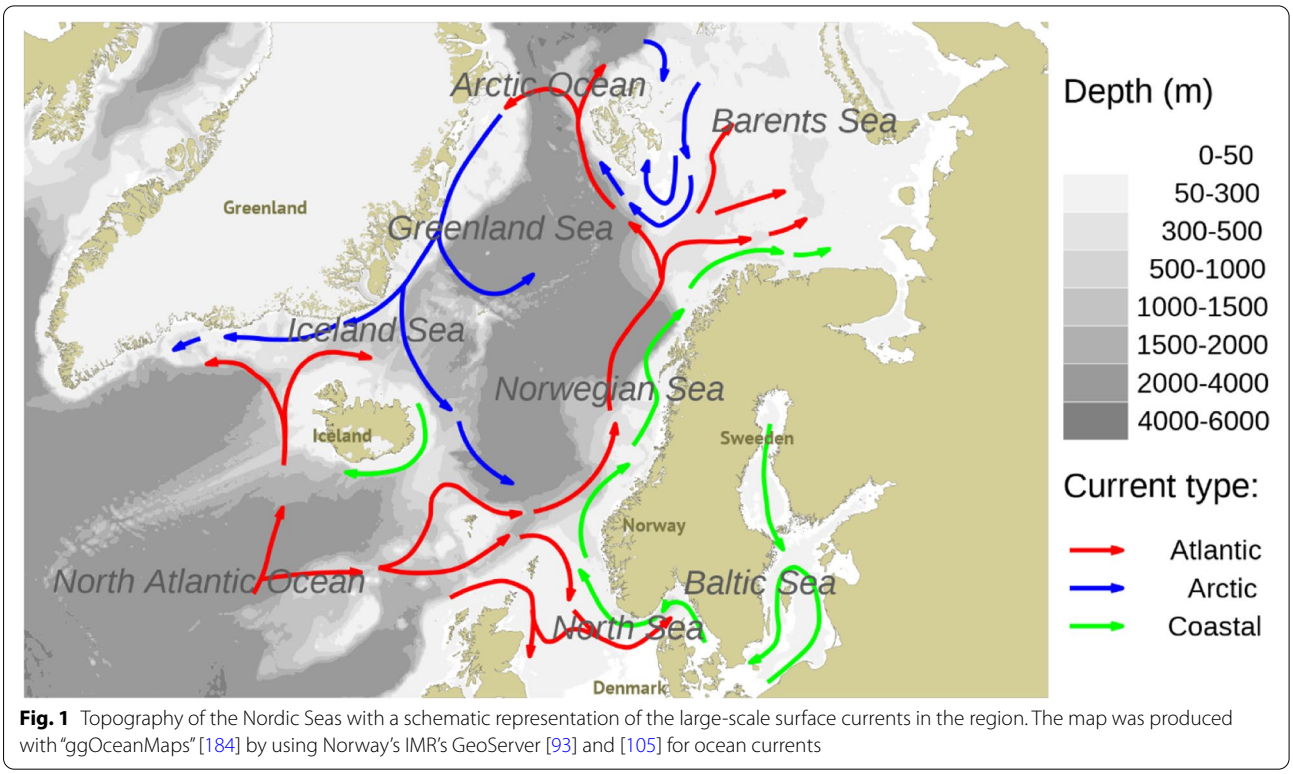

Fig. 1 Topography of the Nordic Seas with a schematic representation of the large-scale surface currents in the region. The map was produced with "ggOceanMaps" [184] by using Norway's IMR's GeoServer [93] and [105] for ocean currents

Table 1 Distinguishing features of the Nordic seas

	Average depth	Oceanography	Species characteristics	Food web characteristics	Contaminant inflow	References
Baltic Sea	60 m	Strong salinity gradients	Small pelagic fish	Structural shifts	From nine surrounding countries	[99, 115, 45, 89]
North Sea	0–500 m	Thermally mixed water column, soft sediments, varied coasts of Kattegat and Skagerrak seas	Herring, sandeel, sprat and Norway pout	Depletion or reduction of larger predatory species and coastal seagrass habitats	Major rivers, south Atlantic currents, and Baltic Sea	[81, 163, 108, 90]
North-East Atlantic	Deep ocean basins, > 1000 m	Entirely oceanic and distant from land	Lack of data, but coral reefs may be habitat for unique species	Simple food webs. Primary productivity is low	Ocean currents bring contaminants and litter from maritime sources	[98, 147, 88]
Norwegian Sea	Two deep basins (3–4000 m deep)	Transition zone driven by the Norwegian Atlantic Current	Increase in mackerel & decline in herring	Complex food web	From western North Atlantic, North Sea, Baltic Sea, Greenland Sea & Barents Sea	[85, 87]
Icelandic waters / Greenland Sea	Below and above 500 m	Coastal shelves influenced by oceanic inputs	Capelin. Immigration of mackerel & herring	Primary production ranges from very low to high	Converging currents, melting ice, local fishing activities	[91, 92]
Barents Sea / Arctic Ocean	230 m	Influx of Atlantic waters	Cod, haddock, capelin, polar cod	Simple with few fish species	Human activities i.e., cargo, tourism & aquaculture	[60, 97, 40, 47, 86]

Table 2 Overview of research questions

Section name	Research question
Sources, sinks and transport	How do oceanographic dynamics determine transport and fate of MPs in the Icelandic waters?
	What sampling designs will best capture spatial and temporal MP distribution patterns in Nordic marine systems?
	Is it possible to determine the relative contribution of MPs from long distance and local sources in the Arctic?
	Is the movement of microplastics in the sea a new type of long-range transport of chemicals, including transport to the Arctic?
Exposure and potential impacts	How do MP particles move through the Nordic marine food webs?
	What are the chemical and immunotoxicological biomarkers of MP exposure in the economically important Baltic herring?
	What are the biological effects of MPs in the Nordic environment?

in the sediment compared to water samples and that the amount of particles varies significantly between sampling sites [164]. The North Sea is highly polluted with MPs where the central North Sea seems to contain the most MPs [140]. Water currents entering the North Sea run along the Swedish west coast and northward along the Norwegian coast into the Norwegian Sea [163]. The Swedish west coast receives both MPs and floating marine litter from the southern Atlantic with the Jutland current, and these shorelines are thus hotspots for plastic pollution [170]. The weathering and fragmentation of beached plastic constitutes are an important, but yet unquantified, source of MPs to the surrounding sea. The Norwegian Sea (Table 1) covers more than 1.1 million km^2 along the Norwegian coast transferring warm saline waters from the Atlantic to the Arctic Ocean [85, 87]. Sea-based MPs source categories relevant to the Norwegian Sea include maritime coatings, maritime traffic, ports, marinas and shipyards, decommissioning activities, land-based industry, fisheries, aquaculture, petroleum-related activities, as well as other offshore activities [125]. Simulated transport of MPs between different marine water bodies in the Norwegian Sea has shown that MPs in seawater on the continental shelf will tend to stay there during winter. However, during summer the winter transport barrier disappears, which allows MPs to spread beyond the shelf [20]. The simulations also showed that the Norwegian Sea is unlikely to become a sink for macro- and microplastic. The North-East Atlantic (Table 1) differs from other ecoregions by being distant from land, making it less influenced by coastal and terrestrial processes [88]. However, much of the coastal area within the North-East Atlantic is densely populated, highly industrialised or intensely used in agriculture [147]. Geostrophic circulation and currents bring high levels of plastic debris to the ecoregion from land-based and maritime sources. This has created a garbage patch in the North-East Atlantic. High amounts of MPs are found in such locations, particularly in the centre of the gyre. The fate of MPs created in such patches, is unknown [143]. The levels of MPs in the North-East Atlantic Ocean are largely undocumented [126]. The Iceland and Greenland Seas (Table 1) are, together with the Norwegian Sea, the main connection between the North Atlantic and the Arctic Ocean [19]. There are two main ocean currents in this area, the East Greenland Current (moving south) and the Greenland Sea Gyre (counter-clockwise circulation). High levels of MPs have been detected in the Greenland Sea Gyre, which seem to contribute to the MP pollution in the surface waters in this ecoregion [96].

The Barents Sea (Table 1) surrounds the Polar Basin and connects the Norwegian Sea, the Arctic Ocean, and the Kara Sea. Oceanic conditions in the Barents Sea and the Arctic Ocean are influenced by the influx of Atlantic waters [86]. A significant environmental threat to these ecoregions is the retreating ice cover, opening new seascapes for anthropogenic activities possibly affecting pollutant levels and biodiversity [97, 86].

Approach to identify research questions

A group of experts with state-of-the-art insight into the current research and policy needs regarding MPs in the Nordic marine environment participated in a workshop organised by the NordMar Plastic network (www.nordmarplastic.com). This workshop addressed knowledge gaps with regards to MPs in the Nordic marine environment, including potential policy relevance of current research needs. The discussions were condensed to a set of key scientific questions. Intentionally, the approach was kept broad, and no ranking of research priorities was performed, to account for the diversity in expertise present at the workshop. The experts were asked to support their prioritised research issue with argumentation why the question is important, what the current state of

knowledge is, how the question could be addressed and who would benefit from the results. Discussions at the workshop aimed to describe specific research questions with little overlap, but with complementary character. The research questions were divided into two categories addressing either "Sources, sinks and transport" or "Exposure and potential impacts" (Table 2).

Research questions

Sources, sinks and transport

How do oceanographic dynamics determine transport and fate of MPs in the Icelandic waters?

The total stock of MPs in the world oceans is a complex mix of particles that stem mostly from various land-based sources associated with human societies [58]. When in the open waters, the distribution of MPs is primarily influenced by ocean currents [36] with areas of accumulation in the world oceans (e.g., ocean gyres), at the surface at least, where MPs can reside for a long time [181, 182].

The circulation of water in the Nordic Seas (Fig. 1) can be described as a large-scale loop with the convective overturning of Atlantic water in higher latitudes [136]. The Nordic Seas have interior gyres over the Norwegian, Greenland and Icelandic Sea basins [112] and, to a lesser extent, in the Barents Sea [119]. Higher abundance of MPs has been found in the Greenland Sea Gyre compared to an adjacent area outside the gyre [96] and a similar situation has been proposed for the Barents Sea Gyre [181]. These gyres do contribute to deep water formation [112] and thereby advection of MPs, from local and distant sources to the ocean floor in the Nordic Seas.

A modelling study [122] found that downward vertical advection played a key role in sinking of small spherical nanoplastic particles (< 1 µm), predicting that for smaller particles the movement of the medium has a larger effect than the particle's buoyancy, since very small particles in water are more affected by viscous forces than inertial forces as is already a well-established fact for other particles in oceanographic and marine biological science [82, 185]. So even positively buoyant MPs can become entrained (stay submerged) once transported to deeper waters [94], and get carried with deep or intermediate water currents. This adds to the level of complexity that simulation models of drifting particles in the ocean column have to take into account.

An understanding of particle transport in the water column and near the ocean floor is complex and not as well documented as horizontal transport at the ocean surface [113, 34]. Furthermore, knowledge on ocean currents and smaller scale perturbations such as eddies, fronts and turbulence is necessary [180]. However, bottom-water circulation processes control sedimentation and create hot-spots for MPs in mounds of sediment on the ocean floor [101]. The sediments in the oceans have been proposed as a sink for MPs [193] and further suggested by Bergmann et al. [17] and Tekman et al. [176] after revealing high abundance of MPs in sediment near Spitzbergen. How and where sedimentation or entrapment of MPs in seabed occurs has been reviewed by Harris [77] but empirical data is still lacking. Weber and Ghaffari [192] states that MPs deposition can also occur on the shelfs and shallow banks in the open ocean due to ocean swells that form because of weather storms. There are indications that MPs in Icelandic sediment are concentrated near the Iceland-Faroe Ridge [124], which is possibly a low energy area of sediment deposition, i.e., where MPs might be sequestered. Large contourite deposits are found on the ocean floor in the Icelandic basin south of Iceland, on the Norwegian basin along the continental margins and west of Spitsbergen [156, 162]. These areas of sedimentation might be areas of interest to study MP accumulation. Because of the patchiness of MPs in sediments, more knowledge on bottom topography and oceanographic processes and increased effort in modelling is necessary to guide targeted MP sampling in these areas.

Simulation of MPs transport and sedimentation of MPs in well-characterised current regimes can visualise hotspots or accumulation zones which in turn may guide sampling efforts in intermediate to deep waters and sediment. A three-dimensional hydrodynamic model [123] was used in studying fish-egg drift [27] within the area of influence of the inflowing Atlantic water to the Nordic Seas, and this could also be applied to simulate MPs transport. The North Icelandic Irminger Current is a continuation of the Gulf Stream that branches off from the Irminger Current and flows to the north of Iceland where it divides further and interacts with coastal and polar water [100] (see Fig. 2). This inflow of Atlantic water seems to dictate the outflowing North Icelandic Jet within an overturning loop completed in approximately one year [152].

The well-researched flow of Atlantic water to the North Icelandic shelf [100], its outflowing counterpart [152], the mixing of different water masses and the known point sources of MPs [168], provides a model system to study how oceanographic conditions drive the transport of MPs in Icelandic waters. Gaining this knowledge would broaden our understanding of how oceanographic dynamics determine the transport and fate of MPs in the Nordic marine environment. Answering this question would provide information to enable authorities and researchers to develop targeted actions to decrease sources of MPs and could be used as the basis for a

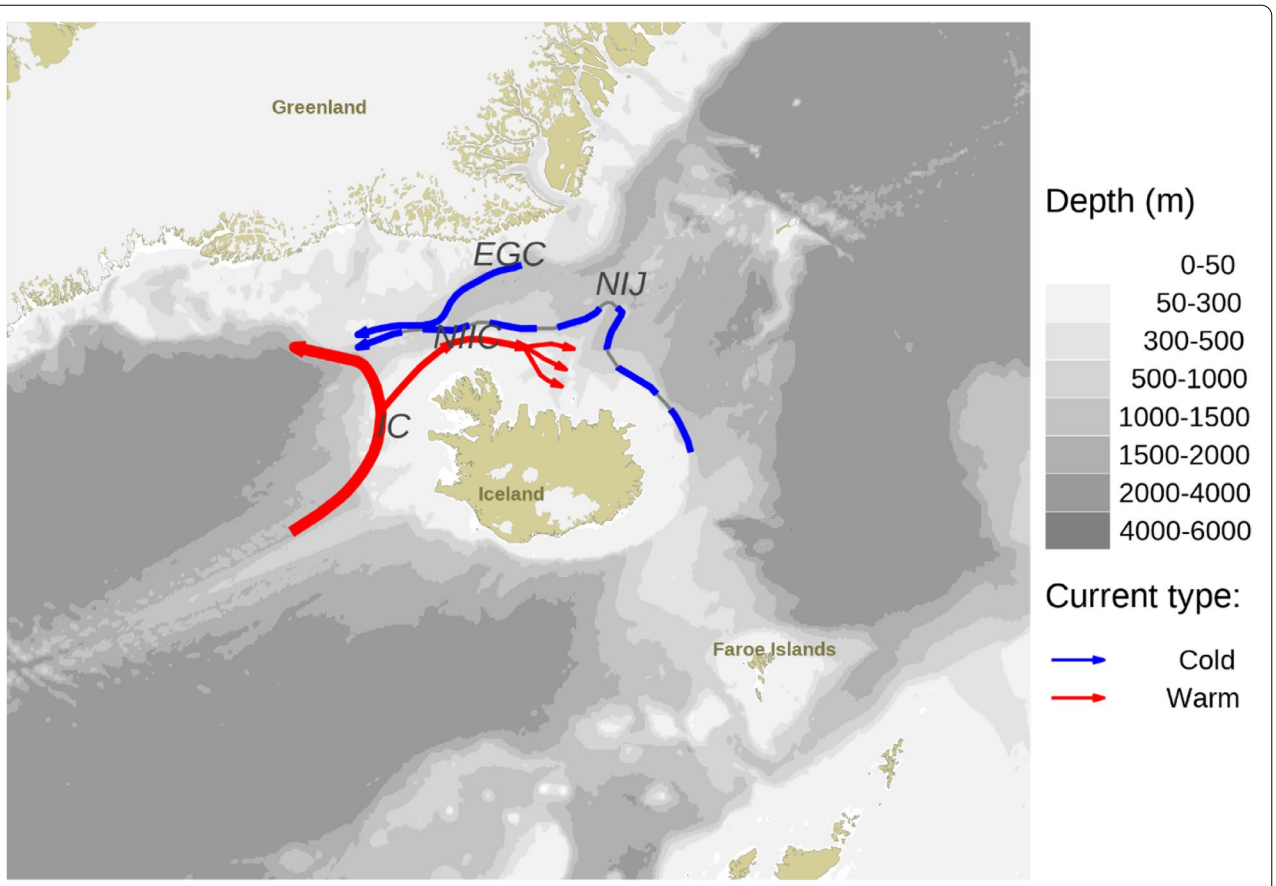

Fig. 2 The North Icelandic Irminger Current is a continuation of the Gulf Stream. It branches off and flows to the north of Iceland where it divides further and interacts with coastal and polar water. Abbrevations: EGC—East Greenland Current, IC—Irminger Current, NIIC—North Icelandic Irminger Current, NIJ—North Icelandic Jet. Solid lines: surface currents, dotted lines: deep currents. The map was produced with "ggOceanMaps" [184] by using [123] for ocean currents

monitoring programme to evaluate the impact of these actions around Iceland and other regions as well.

What sampling designs will best capture spatial and temporal MP distribution patterns in Nordic marine systems?

Most studies begin their discussion of 'sampling methods' for MPs at the level of the environmental sample itself, how to obtain it (sampling gear, volume), and which method is most appropriate and reliable to correctly quantify the number of MPs in it (laboratory quantification and identification). This can be a sample from the sea surface, the water column, the seafloor sediment, beach, or a marine organism. How the total number of samples was decided upon, however, and how sampling stations should be distributed along geographical and temporal scales in a specific target area, is rarely discussed. Sampling strategies are often restricted to either the sea surface (Manta net), a single depth (underway sampling or systems on ships) or the bottom (sediment grabs), or a preferred organism (e.g., blue mussel, Arctic fulmar).

To establish concentration maps of MPs and inform regional extrapolations and numerical models of MP distributions from limited field sampling, better sampling designs (how much, how often, how many, how deep?) need to be developed to enable predictions and test mitigation scenarios. It is known that different sampling techniques (e.g., bulk pump samples versus volume-reduced Manta net samples) will produce different results in terms of measured MP concentration per volume sea water [174]. Similarly, chosen mesh sizes and/or indicator organisms will target certain size spectra or types of MPs [35]. Here, these differences will be ignored, as they will eventually be eliminated when standardised, or at least harmonised, techniques will be agreed upon and be used consistently in monitoring approaches [59, 3]. High numbers of replicates reduce MP abundance variation within sample location or timepoint [35, 174], and a minimum of 5 replicates has been recommended to

reduce this variation [174]. Small volumes are suitable to determine the smallest MPs, as very fine mesh sizes can be applied to target particles ≤ 10 µm [35]. This may be useful in locations with high contamination levels, but restricted space for sampling, such as harbours and ports [39], or near point sources, such as wastewater outlets or marine installations, but requires a sufficient number of samples per area and total depth to account for possible spatial variation.

A number of papers present MP distributions at regional scale [127, 167, 37, 68], while others attempt to pinpoint local sources [172, 125, 171], or identify MP signatures of oceanographic domains [75], but no systematic analysis of regional patterns and trends exists for the Nordic Seas.

Studies that map and characterise MP distribution patterns are scarce in relation to the vast ocean areas contaminated with MP to various degrees. Knowledge of local sources is often restricted to local reports (e.g., Sundt et al. [172], Lusher and Pettersen [125], while modelling studies cannot be based on realistic extrapolations of measured MP concentrations and gradients [76, 189]. Research efforts tried to simplify this complexity by concentrating the focus on the most likely environmental compartments where MPs may accumulate or be abundant: sea surface waters were targeted with Manta net sampling in the earliest studies, as low-density plastics are buoyant and expected to float in the upper centimetres of the water column [42]. With the realisation that certain combinations of physical properties of MP, oceanographic dynamics (How do oceanographic dynamics determine transport and fate of MPs in the Icelandic waters?), and biological processes will make MP sink, even those with low density, sediments were suggested as a better alternative. Soft-bottom habitats were hence sampled with grabs or dedicated MPs sediment samplers [80], as all MPs were expected to sink to the seafloor eventually [193]. Another alternative discussed as suitable MPs distribution indicator is biota known to ingest MPs, e.g., bivalves [117], fish [129], or seabirds [41], where stomach contents collected along latitudinal or other gradients may give indications of MP pollution trends. This, however, does not fully represent MP distribution in the entire marine environment,important compartments (e.g., most of the subsurface water column) are left out, and snapshot sampling conducted in one place at one point in time may neither be representative of different seasons, nor across a larger area, i.e., scales of spatio-temporal variation in MP distributions are largely unknown. A high-resolution modelling study of MP fibre distribution in an Arctic fjord upon release from a single wastewater point source revealed that within 100 h MP fibres distributed very differently in the fjord depending on their physical properties (here density). While light, low-density fibres were transported out of the fjord within a few tidal cycles, heavy fibres deposited on the seafloor of the inner fjord and accumulated there [79]. Although this needs verification through ground-truthing from actual sampling, it shows the fast pace of MP distribution changes in a relatively small area, as well as the importance of hydrodynamics for local accumulation.

A meta-analysis of existing studies of MP distributions should be conducted with a view to designing sampling strategies that take horizontal and vertical variation in MP distribution and potential drivers of these distributions into account, or – where such information is missing to date—adopt existing sampling strategies for other, well studied marine particles (e.g., plankton, marine snow, sediment, benthos) [131, 173]. Mapping of existing data and identification of drivers of MP particle distribution across the Nordic Seas may provide a regional picture of MP pollution gradients that can facilitate the development of suitable sampling designs [59, 3]. Rather than using static station transects or grids, choosing more flexible sampling approaches that take e.g., topography, depth, or volume of the targeted water body and abiotic and biotic drivers of MP distribution into account may be beneficial to resolve spatial patterns. We thus suggest the following considerations prior to sampling:

I. Spatial factors

1. Definition of scale: it is expected that for a basin-scale or latitudinal study fewer sampling points and/or large volume underway sampling at larger distance intervals will be adequate [104], as they represent water bodies with relatively low MP abundances and more uniform MP signatures, after advection, dilution, convection and vertical mixing processes have taken place upon entry into the marine environment. Indeed, a recent study concludes that modelled marine MP concentrations across the Arctic Mediterranean are at a 'saturation equilibrium' reflecting decades of MP advection [84]. Near point sources, such as wastewater outlets [79] or harbours [39] etc., small scale local sampling with a finer resolution of sampling points is required due to steeper MP gradients away from the source(s), while input from rivers and estuaries, as well as metropolitan cities, and analysis of MP distribution in mesoscale oceanographic features (e.g., eddies) will benefit from sampling at an intermediate spatial scale.
2. Analysis of coastal use in the target area: along the Scandinavian coasts various MP sources have been identified, ranging from offshore installations for

oil and gas, aquaculture installations to commercial and industrial activities onshore. The distribution of these sources along the Nordic Seas coastline can guide sampling efforts similar to the approach by Jang et al. [95].

3. Based on the above, sampling schemes should endeavour to discern local input of new MP emissions from 'background contamination' arriving with long-range transport or long-term exposure at location, e.g., based on the proportions of weathered versus pristine MP [22], specific MP-watermass signatures, see also Is it possible to determine the relative contribution of microplastics from long distance and local sources in the Arctic?, and estimates of local MP displacement and transport [79].

4. Gradients perpendicular to the coastline from land to ocean habitats (beach, intertidal to offshore; estuary to offshore) near likely emission sites will uncover sources from plastic production/usage/disposal sites on land (direct input to the sea or through river transport).

5. Stratified sampling throughout the water column: Sub-surface processes are not captured by surface or sediment sampling alone, while the water column encompasses most of the ocean volume and thus a major proportion of the MP pollution. Many pelagic organisms may be exposed in sub-surface layers. A recent modelling study shows differential behaviour of MPs with different densities [79], and biofouling and other physical processes will determine the vertical position of MP (degradation, aggregation, biofouling, viscosity, etc.), see also How do oceanographic dynamics determine transport and fate of MPs in the Icelandic waters?.

II. Temporal factors

1. Tidal cycles and oceanographic features: Locations with significant tidal ranges need frequent sampling at different tides to resolve transport and deposition patterns relating to the tides at daily and monthly intervals.

2. Recurring features or events: Meteorological and biological seasonal events may have significant impact on MP transport and distribution. These may include e.g., prevailing wind directions and storms, especially near the surface and possibly against the prevailing current regime, versus stratified periods during calm, stable weather, seasonally changing biota assemblages (e.g., phytoplankton blooms or jellyfish aggregations), or particulate organic matter (POM) input from land. Human interventions such as singular inputs from shipping (lost load) or tourism (littering from cruise ships or coastal attractions) could also fall into this category.

Answering this question will be useful for both design of field research and monitoring purposes, since better sampling designs will be essential in the planning of both research projects aiming to better understand MP distribution, transport, and trends, as well as monitoring programs with the goal of demonstrating mitigation measure success over time.

Is it possible to determine the relative contribution of microplastics from long distance and local sources in the Arctic?

Little is known about the origin, fate and mechanisms driving the distribution of Arctic marine MP pollution [148, 159]. Because the Arctic is sparsely populated and remote, the entrenched view has been that pollution is not generated there but transported to the Arctic from more densely populated and industrialised regions [130, 50]. This fate is true for many persistent chemical pollutants, however some of the most locally polluted sites of the world can be found within the Arctic [1, 66]. Because these sites (e.g., abandoned mines, oil drilling sites and military installations) are impossible to decontaminate and restore, they are often left and forgotten and some are even protected as cultural heritage sites today [66]. These and e.g., current industrial waste and discharges as well as waste and wastewater from local communities constitute important local pollution sources of both chemicals and plastics in the Arctic [69, 186, 79].

Based on the idea that Arctic pollution has an external origin, the main approach to investigate sources of plastic pollution in the Arctic has been to study the long-range transport of MPs via water- and recently air currents using modelling tools [181, 114, 49, 120]. To test the models, measurements of marine plastic pollution have been conducted in strategic offshore areas, like the Fram strait [16, 176], and where water masses meet or slow down [127, 37, 103, 83]. Another reason for studying plastic pollution in offshore areas is that Arctic marine research often is carried out from large research vessels unable to travel in shallow coastal waters. This has most likely created a bias in our current knowledge on the sources of MP pollution in the Arctic. When it comes to coastal plastic pollution, great efforts have been made to map and investigate marine debris on Arctic beaches [153, 15 , 109, 183] and attribute beached plastic litter items to sources and countries of origin [52]. Less attention has been given to shallow coastal waters where land-sea or river-sea interactions are strong and local land-based discharges can be specifically targeted.

Although local sources and pathways, e.g., rivers [177, 57, 197], wastewater effluents [132, 64, 186, 79], garbage dumping sites [65], and industries [68, 128] may contribute significantly to marine plastic pollution in the Arctic we have little knowledge about the quantity and quality of plastic pollution originating from them. One approach to distinguishing different sources can be to measure typical signatures of MPs in a given water mass [127, 135]. MP compositions have been observed to differ between water masses, sediment types and environmental matrices where, e.g., sea ice contains more fragments [150, 102, 186] than seawater, which is often dominated by fibres [127, 186, 120, 159]. Beach sand contains a higher proportion of fibres (90%) than both tidal (49%) and estuarine (57%) sediments [77]. In an extensive study, Yakushev et al. [197] investigated MP pollution in surface and subsurface waters at varying distance from the plumes of the Great Siberian Rivers. The authors concluded that marine-borne (remote source) and river-borne (local source) MPs had distinctly different physical (size, morphology, weight) and chemical (polymer type) characteristics, making the different water masses statistically distinguishable from each other. Lusher et al. [127] reported up to a tenfold difference in MP concentrations between water masses originating from the Atlantic and Polar seas, respectively. The concentrations and composition of MPs (sizes, morphological features, polymers) in different environmental matrices depend on intrinsic factors of the MPs as well as on external abiotic (e.g., hydrodynamics, temperature, salinity, concentration of other particles) and biotic (e.g., biofouling, species composition, season) factors [195, 77, 13]. The "fate pathway" of MPs is key to linking MP composition of a matrix to its source.

The composition and quantity of marine MP pollution should be characterised as close to the source as possible, e.g., in wastewater effluents, run-off from garbage dumping sites, polluted beaches, ice edges etc. It is important to identify the sources feeding into the pathways where, e.g., the river is a pathway carrying the MPs originating from various sources, i.e., products and processes, to the sea. Understanding the type of MP pollution generated by various products or processes is thus also important and existing information from other parts of the world may be a good starting point here. Different water masses appear to carry the MP signature or "fingerprint" of their origin [127, 95, 186, 197] and their distribution should thus be mapped to provide a comprehensive picture of MPs fate related to source. Oceanographic parameters (temperature, salinity, pigments, and other tracers) characteristic of, e.g., Atlantic, Pacific, riverine or Polar water masses should be measured simultaneously to support interpretation of origin and movement. This work can preferably lead to the construction of MP fingerprint libraries characteristic of specific sources or origins. If it is possible to link the MP fingerprint to a specific source or origin, emission responsibility and mitigation efforts can be identified, which in turn will enable managers and policy makers to implement measures to restrict pollution. This would be important information for e.g., industries, municipalities, regions, and countries. Answering this question is central to guiding management actions and introducing effective policy measures to reduce marine microplastic pollution. This question is also applicable to other regions but may be region-specific due to the presence of unique sources.

Is the movement of microplastics in the sea a new type of long-range transport of chemicals, including transport to the Arctic?

The long-range transport of chemicals is one of four criteria for their classification as persistent organic pollutants (POPs) according to the United Nations Stockholm Convention, the others being persistence, bioaccumulation and (eco)toxicity [178]. The presence of chemicals in remote areas of the Arctic has served as an indicator of long-range transport in the risk profiles for candidate POPs. Many POPs are semi-volatile organic compounds and mainly transported to the Arctic in the atmosphere [190, 63]. However, for some compounds, such as β-HCH and perfluorooctane sulfonate (PFOS), the transport with ocean currents is the primary pathway [118, 199]. Vector-based transport of chemicals, for example with migratory animals, is well-known and recognised in the Stockholm Convention [178, 187]. Plastic litter and MPs are also known to be transported over long distances [143], and with them the chemicals that are added to plastic polymers to obtain and ensure certain functionality, as also recently addressed by Andrade et al. [5]. Additives include, but are not limited to, plasticisers, flame retardants, antioxidants and UV-stabilisers, lubricants and colorants [72, 5]. UV-328 is a substituted phenolic benzotriazole used as a UV absorber in plastics and other products. It was recently proposed as a candidate for the Stockholm Convention, including a justification of its long-range transport via plastic particles [179]. If the transport of chemicals with a plastic particle is regarded as long-range transport, it will likely apply to multiple chemicals. Therefore, it is important to characterise it better, qualitatively and quantitatively, for plastic particles as abundant vectors.

The occurrence of litter and MPs in the Arctic can be related to ocean, riverine and atmospheric transport from distant sources, as well as to emissions within the Arctic region itself [148], as discussed in more detail in Is it possible to determine the relative contribution of

microplastics from long distance and local sources in the Arctic?. The presence of ice which temporarily retains MP particles, is also of significance for the transport within the Arctic [142, 150].

As discussed in Is it possible to determine the relative contribution of microplastics from long distance and local sources in the Arctic?, the transport pathways of MPs to and in the Arctic and the relative importance of local and distant sources is not well-understood. Furthermore, limited information is available on the identity and amount of chemicals present in different types of plastic material. Some information is proprietary knowledge, but due to complex trade structures, information may generally be difficult to retrieve. Given the long lifetime of plastic materials, a relatively large time span will have to be covered, potentially including chemicals that have been taken off the market in recent years. In addition to additives, unreacted monomers from the production process can be left in the plastic polymers [121]. Furthermore, the content of chemicals in a plastic product is likely to change over time, as an effect of equilibration processes, but further influenced by the physical, chemical, and biological weathering of the plastic particle. As weathering proceeds, affecting the structure of the particle, it presumably favours the leaching of chemicals. However, leaching rates likely depend on the physical–chemical properties of the chemical, i.e., they differ between chemicals and between plastic materials, as well as on environmental conditions. Because of these knowledge gaps, a quantitative description of the long-range transport of chemicals with microplastic particles is challenging, involving a number of assumptions [5] Actual measurements of chemicals in plastic particles are sparse, in particular for the Arctic, as recently reviewed by Fauser et al. [56].

Closing the current knowledge gaps would require more knowledge of the amount of microplastics in the Arctic, their sources and transport pathways to the Arctic, their content of chemicals and influences of weathering on chemical contents. This information should be derived from measurements in combination with modelling approaches describing MP transport, as discussed in What sampling designs will best capture spatial and temporal MP distribution patterns in Nordic marine systems? and Is it possible to determine the relative contribution of microplastics from long distance and local sources in the Arctic?. As a first step, polymer-specific occurrence data on MPs in the marine environment of the Arctic are required, primarily in the water phase as the main medium for long-range transport of MP. However, understanding the role of the atmosphere and the cryosphere in the transport and accumulation of microplastics in the Arctic needs more research and should be considered to the extent possible, for example as outlined by Hamilton et al. [74]. While monitoring of litter and MPs in the Arctic is being initiated [3], quantitative data will likely be patchy and limit the geographical scope of addressing this question. Secondly, source apportionment is needed to distinguish between locally emitted plastics and long-range transport, as also discussed in Is it possible to determine the relative contribution of microplastics from long distance and local sources in the Arctic?. The modelling of transport pathways, based on known source areas and oceanographic models, would be helpful in discussing to what extent microplastic particles are emitted locally or more likely to be transported from long distances [189, 138].

While more and more studies address chemical additives and other residues in plastics in the environment, knowledge of chemicals in plastics is still and challenged by the large number of potential additives [72]. In addition to data collection from producers or trade organisations [55], new non-target or suspect screening techniques in analytical chemistry could provide indications of the presence of chemicals in plastic particles [8]. These approaches typically aim at an identification of chemicals, rather than a quantification for which an analytical standard of a known concentration will be required. Again, qualitative approaches appear more achievable than quantitative approaches. If the identity of a chemical is known and an analytical standard is available, targeted quantitative methods can be established, but will require method development and validation as microplastics are not yet an established environmental matrix in analytical laboratories. We therefore also recommend further developments in analytical chemistry, with a view to identifying, possibly via non-target screening approaches, and quantifying additives and other residuals in plastic particles, including quality assurance/quality control (QA/QC) measures.

While the chemical analysis of microplastics from Arctic samples would provide data on the chemical content *in situ*, it would be helpful for qualitative as well as for quantitative assessments to better understand the leaching of chemicals from the plastic material over time, as recently discussed by Fauser et al. [56]. Focused laboratory studies under controlled conditions are recommendable for a better understanding and description of this process. Better knowledge of the effect of weathering on the chemical content of additives in plastics, and their leaching behaviour, would also improve the possibilities of modelling these processes and thus, enabling extrapolations in time and space. Finally, following, if possible, a quantitative description of the long-range transport of selected chemicals with microplastics to the Arctic, it would be relevant to compare these with model outputs

describing the long-range transport of well-known POPs [63], to assess the significance of this transport pathway.

Answering this question is of high importance for policymakers in the context of reviewing POP properties of UV-328 under the Stockholm Convention. Furthermore, the ministers of the Arctic States stated in the Fairbank Declaration "growing concerns related to the increasing levels of microplastics in the Arctic" and "welcome the work on Chemicals of Emerging Arctic Concern, addressing new potential persistent organic pollutants and other pollutants" [6]. Important stakeholders that would benefit from this type of study are also local and indigenous communities in the Arctic whose food safety should be ensured through early recognition of potential new sources of contaminants [4].

Exposure and potential impacts

How do microplastic particles move through the Nordic marine food webs?

Knowledge on mechanisms controlling uptake of MP particles of different size and shape categories from the surrounding environment into organisms and potential subsequent egestion is important when assessing exposure to MPs. If the uptake rate is greater than the rate of elimination, MPs bioaccumulate, with potential health and fitness implications for the individual and possible upscaling effects through populations and ecological communities. Knowledge of trophic transfer of MPs from primary consumers (e.g., copepods) to higher trophic levels in the marine food web (biomagnification) is important for assessing health risk to top predators and for performing assessments of food safety of commercially important marine species (e.g., fish, shrimps, shellfish) What are the biological effects of MPs in the Nordic environment?.

MPs have been found in the different trophic levels from micro- and macro-algae, benthic and pelagic invertebrates and fish to top predators, such as seals [127, 24, 141, 148, 25, 110, 137, 151, 198]. Biofilms on the MP surface can increase the uptake of MPs [188] in filter feeders, but some filtering organisms, e.g., bivalves separate MPs from food and can egest them as faeces or pseudo-faeces [194, 191]. Egested MP particles can be packed together with organic material in faecal pellets [32] and may be taken up by other organisms in the food chain. As discussed in Is the movement of microplastics in the sea a new type of long-range transport of chemicals, including transport to the Arctic? , the emission of plastics to the marine environment can lead to leaching of chemicals to seawater or, after uptake of a plastic particle, in the gut of an organism (What are the biological effects of MPs in the Nordic environment?). A recent literature review supports that bioaccumulation of MPs occurs in organisms within different trophic levels, while this is less clear for bioaccumulation of associated chemical additives [137]. A recent study demonstrates the plasticiser bis(2-ethylhexyl) phthalate (DEHP) to be present in blubber of marine mammals from the Norwegian Arctic [160], however, the sources could not be clearly identified and were more likely to be related to plankton ingestion than to exposure to plastics [23, 161, 11, 144]. Some laboratory studies supported trophic transfer, although the unrealistically high doses used warrant more studies to evaluate such processes under more environmentally realistic conditions [137]. Many studies have been published on uptake of MPs in the Nordic marine food web [23, 161, 11, 144], while knowledge on bioaccumulation is missing and if this leads to biomagnification [54, 141, 62]. Observations from field-based studies report that MP particles are located within the gastrointestinal tract [62], but appropriate methods to target the smallest particles that are able to be assimilated and pass over membranes are only now emerging [61].

One key species in the food webs of the Nordic Seas are copepods of the genus *Calanus* channelling nutrients and lipids to a range of higher trophic organisms feeding in pelagic water, including fish larvae, pelagic fishes, baleen whales and birds [14]. *C. finmarchicus* is the dominating species in the North Sea, the Norwegian Sea and the Barents Sea, while *C. glacialis* is dominating in Arctic waters and *C. helgolandicus* more abundant in southern parts of the North Sea.

Exposures to high concentrations of MPs (75–100 MPs mL^{-1}) have shown decreased reproductive output of the copepods due to competitive ingestion of microalgae and MPs [31, 33]. Although these concentrations are higher than what is expected as environmentally realistic, negative energetic effects at the individual level may be anticipated in highly contaminated areas. At early life stages, some fish larvae are known to be highly sensitive to nanoplastics and MPs [30, 149, 196]. However, information is lacking on threshold levels of toxicological effects for *Calanus* species and fish larvae of e.g., herring, cod, and other important fish species from the different ecoregions in the Nordic seas (Table 1 and What are the biological effects of MPs in the Nordic environment?). Such information is needed to be able to perform risk assessments for key species in the food web and the functioning of trophic chains in the different regions. Controlled exposure studies that cover uptake in zooplankton and fish larvae of the most important species in the main ecoregions of the Nordic Seas would give information of trophic transfer and would be valuable input for modelling such processes and evaluate possible impacts at a larger scale.

Answering this question would lead to improved risk assessments on which levels of MPs that may give toxicological effects and affect ecosystem function and services. We believe such knowledge would lead to advice-focused actions to reduce discharges. It would benefit stakeholders responsible to ensure good environmental status and food safety at national and international levels (EFSA, ICES, OSPAR, EU, AMAP and national authorities), in addition to NGOs and the public in the Nordic countries.

What are the chemical and immunotoxicological biomarkers of microplastic exposure in the economically important Baltic herring?

Since the 1970s, experts in the field of ecotoxicology have become increasingly aware of the adverse effects of environmental contaminants on the immune systems of animals. Baltic herring (*Clupea harengus membras*) is a secondary predator known to consume microplastic in its diet [144]. Not only does herring play a key ecological role in the Baltic Sea, it is also a commercially important fish species for human consumption. Amongst the adverse effects from uptake of MP particles, especially fibres and nanoparticles, and their accumulation in fish organs (e.g., gills), immunotoxicological responses to MP exposure need to be considered.

The analytical techniques for detection of nanoparticles of plastic have only recently started to become available after years of ongoing development [10, 29, 28]. The low micron and submicron particle sizes are relevant for immunotoxicological studies because these are the most bioavailable and may interact with the immune system cells of the fish. The new mass spectrometry-based techniques, and combinations of electron microscopy and Raman or atomic force microscopy, among others, are pushing the detection limits of MPs in tissues and target also the nanometre size ranges that have eluded most of the microplastics research to date [9].

Indications of immunotoxic responses to MP uptake in fish exist [67, 48], but immunotoxicity has not yet been studied for Baltic herring, even though fish immunology is an established field [157]. Innate immune responses and immunosuppressive effects of various environmental contaminants on fish have been the subject of study (241 publications reviewed in Rehberger et al., 2017 [157] and the techniques, including the analysis of immunotoxicity biomarkers, such as antioxidant activity and antibody formation, are available to test MP effects. It is important to understand both the risks to the fish itself, the risks associated with secondary poisoning, i.e. the indirect exposure through contaminated food (e.g., in seals feeding on fish containing MPs) and the potential risks to humans as consumers of Baltic herring, including potential immunotoxicological effects in both.

Mechanisms of particle and fibre toxicity involve, e.g., oxidative stress and inflammation [70]. Plastic particle pro-inflammatory effects, i.e., an altered or exaggerated inflammation response, have also been shown, although not for the Baltic herring [169]. Regarding MP loads in fish tissue, only few studies are available, e.g., that of Ribeiro et al. [158], who found 0.3 mg plastic per gram tissue in sardines. More is known about large particles present in the gut contents of fish, giving an indication of the exposure and/or distribution of large particles. A recent review, covering close to 100 publications between 1972 and 2019, reported plastic ingestion in wild marine fish from all over the world for 65% of the 494 examined species [134]. The rate was similar (67%) for commercially important fish species [134]. However, various method-related biases were noted, for example related to sample sizes and detection methods, and immunotoxicological effects are not usually evaluated in studies on plastic in gut content.

Any study of plastic particle effect should measure both the internal exposure (tissue abundance/concentration, near the site of toxic action) and immunotoxicological biomarkers, such as antioxidant activity and antibody formation [157].

Part of the necessary work is to analyse samples of fish collected in the field, to establish MP concentrations in tissue down to the low nanometer particle sizes. The analysis should establish MP presence in wild fish tissues in terms of exposure per monomer and/or polymer type, as described above. The immunotoxicological part of the study, i.e. the measurements of biomarkers of immunotoxicity in response to MP and nanoplastic exposure, would take place in the laboratory using established assays from the fish immunotoxicology field [157]. This field work would ideally be supported by studies of dose–response-relationships under controlled laboratory conditions. Answering this question is crucial for ecological risk assessment of MPs and nanoplastics. The aspect of transfer of MPs up in the food chain and potential human exposure and associated effects also ties into the questions of biomagnification discussed in How do microplastic particles move through the Nordic marine food webs?. Answering this question would be important for scientists, policy makers as well as risk assessors to e.g., set toxicologically relevant maximum levels for MPs and nanoplastics in seawater and seafood to qualify for good environmental status [139].

What are the biological effects of MPs in the Nordic environment?

Biological effects of MPs have been shown in multiple marine and freshwater species as reviewed by Bucci et al. [26], Haegerbaeumer et al. [71] and Kögel et al. [110]. Commonly reported effects include reduced individual

and population growth, behavioural alterations, oxidative stress, inflammation, immune responses, hormonal regulation, aberrant development, increased rates of cell death, and altered lipid metabolism [71, 26, 110].

As discussed in Is the movement of microplastics in the sea a new type of long-range transport of chemicals, including transport to the Arctic? and How do microplastic particles move through the Nordic marine food webs?, an exposure to MPs can go along with an exposure to MP-associated chemicals. In addition to direct exposure through ingestion of a plastic particle, indirect exposure can take place via leaching of chemicals from plastics to the environment and subsequent uptake with water or prey [56]. Current evidence suggests that hydrophobic chemicals leach into seawater to a minor extent, while leaching to oily substances in the gut of an animal could be a significant process [175]. However, ubiquitous hydrophobic chemicals are also taken up with prey, described as secondary poisoning in What are the chemical and immunotoxicological biomarkers of microplastic exposure in the economically important Baltic herring?. According to Miller et al. [137], the uptake of chemicals from the environment, including the food chain, seems to be a stronger contributor to bioaccumulation of these chemicals than the direct exposure to plastic-associated chemicals. Effects and risks associated with an exposure to chemicals should be separated from effects and risks associated with the exposure to MPs alone [106].

MPs can be considered an emerging contaminant in the Arctic and Nordic environment [2, 73]. Low temperatures such as those of the Arctic and Nordic marine environments are known to affect physical–chemical properties of contaminants [106] as well as biological processes, usually lowering solubility and degradability of compounds. Environmental fate processes, e.g., leaching of chemicals from a plastic particle, might have to be adjusted for cold regions. Further, the majority of laboratory exposure and effect studies have been performed at temperate temperatures and might thus not be transferable from temperate to cold regions. Experimental studies also tend to use high concentrations of MPs for short exposure times, which does not correspond to real environmental conditions [71, 26, 110]. As such, very little information is available on whether relevant environmental concentrations of MPs such as reported by Beiras and Schönemann [12] and Everaert et al. [51], can produce physiological responses in biota during long term or chronic exposure [38, 12].

There is hence a need for exposure and effect studies on North Atlantic organisms under realistic MP concentration scenarios. When conducting exposure studies great care should be taken to simulate environmental conditions in the laboratory and use representative MP types (e.g., size, polymer, and weathering state), preferably in the medium that organisms were collected from. Creating turbulence in the exposure tanks may induce more realistic MP distributions than static set-ups. Aggregation of MPs should also be taken into account as it affects encounter rates, where increased dilution reduces aggregation [145]. Potential interactions of MPs with natural particles [116] are little studied, i.e., if and how they aggregate and whether this leads to a decrease or increase in exposure and/or toxicity [7].

Marine biota thrive in an environment filled with particulate matter and have adapted means to prevent unwanted particles from entering their bodies (e.g., selective feeding), facilitate their excretion in faeces, or exhibit internal isolation (e.g., pearl formation). To answer whether MPs are causing effects in Nordic marine biota, there is a need to study interactions of local marine biota with both naturally occurring and synthetic particles on the physiological level. The first step would be to identify which species or specific life stages are sensitive to MPs through biological endpoints such as reproductive success, oxidative stress, or aberrant behaviours reducing fitness, to differentiate between the effects of natural particles and MPs. In this respect, it is important to consider that physical properties of MPs such as polymer type, shape and condition (weathering state, electrical charge, chemical composition) appear to be important factors in biota-particle interactions [71, 26, 110]. Such an experimental approach could build on already available literature (reviewed by Besseling et al. [18] and Bucci et al. [26] and be applied for species that are currently known to be exposed to MPs in the Nordic environment (see How do microplastic particles move through the Nordic marine food webs?). The results could provide threshold levels for selected MPs and species in Nordic environments. Answering this question would lead to a better understanding of the risks that MPs pose to Nordic marine ecosystems. Knowledge gained would thus be important for formulation of ecological risk assessment in the Nordic regions by discriminating specific MPs as stressors and identifying relevant endpoints.

Conclusion

To prepare this paper experts in the field of MP research were gathered to identify Nordic sea-specific knowledge gaps and unanswered questions (Table 2) regarding MPs in the Nordic marine environment (Fig. 1 and Table 1). The experts reviewed state-of-the-art knowledge from the Nordic regions as well as other regions to formulate suggestions on how to approach the knowledge gaps, and/or recommendations (Fig. 3) for the next steps in Nordic MPs research. Concrete examples were put forth to invite discussion

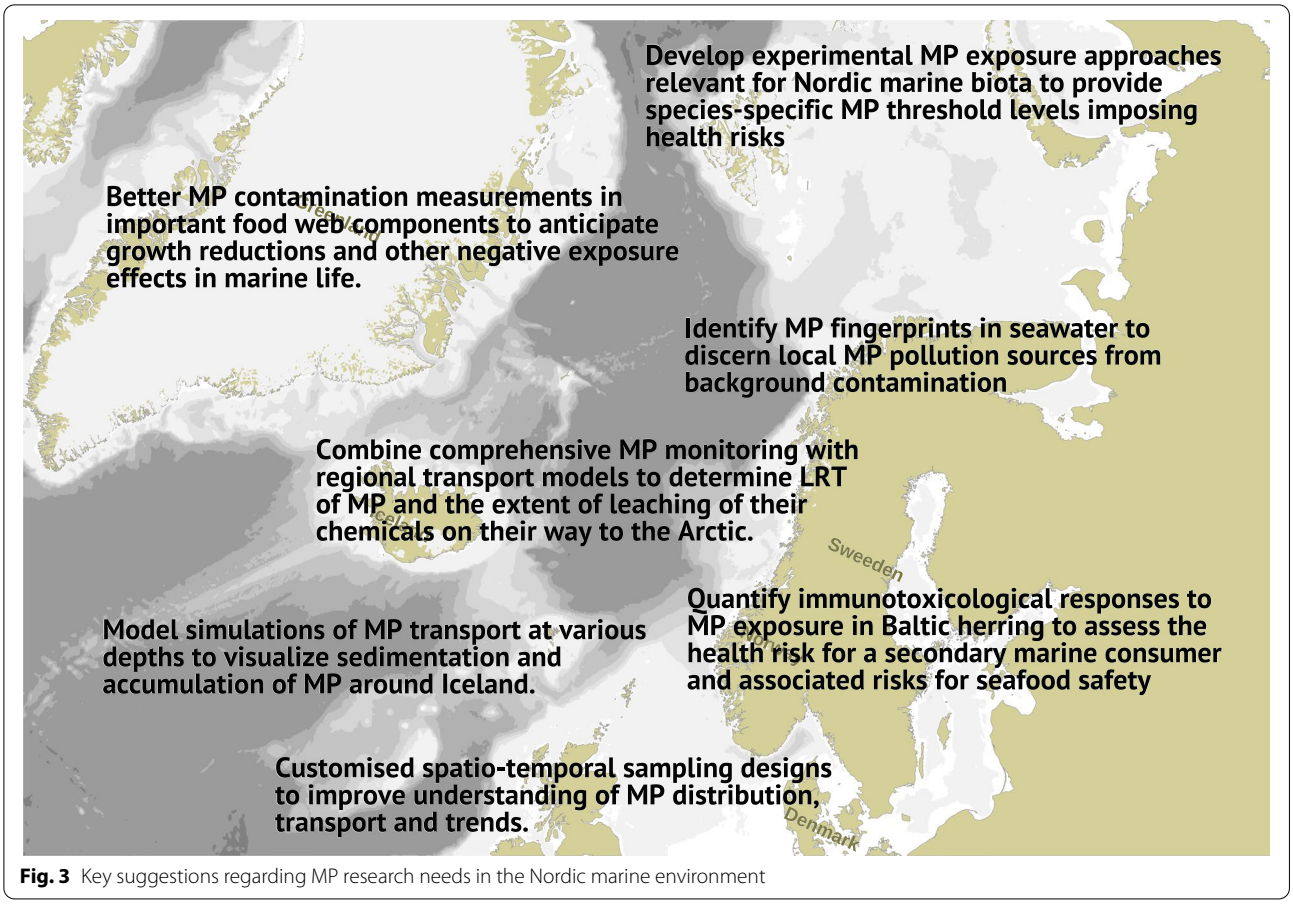

Fig. 3 Key suggestions regarding MP research needs in the Nordic marine environment

on how a concerted effort by the Nordic countries can bring MP research to a higher level of understanding needed to address the MP pollution problem in Nordic marine habitats. From this exercise it is evident that there is a need for further studies to describe the current situation more accurately (i.e., the extent of MP pollution and associated chemical pollution in the Nordic Seas and expected environmental problems) to try to predict the future. Funding of such studies and international collaboration of research groups is key to develop the Nordic MPs research field further and for building a better foundation for policy makers and risk assessors to take decisions. The knowledge acquired from answering the research questions raised within this paper can be used as a basis for guidance of management actions and introduction of effective policy measures, based on risk assessments, to reduce marine MP pollution. Although the relative importance of local and distant sources is not well-understood, the amount of plastic being released into the Nordic marine environment is underlining the importance to reduce MP emissions, both locally and from long-range transport. If it is possible to link the MPs to a specific source or origin, emission responsibility and mitigation efforts can be identified, which in turn will enable managers and policy makers to implement measures that can restrict pollution. Even though there are mitigation actions ongoing, such as EU´s ban on single use plastic (Directive (EU) 2019/904), more actions are needed and further emphasis on research is called for, especially on instrumentation, toxicology and ecotoxicology and risk assessment. The Nordic countries have a long history of collaboration and could use this as a strength, combining infrastructure and knowledge to further focus on MP research, which could produce approaches with global applicability. The Nordic Council of Ministers could build on this strong cooperation e.g., with formation of a Centre of Excellence on plastic research, ensuring funding for broad Nordic plastic research and thereby strengthening the Nordic research cooperation as well as cooperation internationally.

Abbreviations
AMAP: Arctic Monitoring and Assessment Programme; ECHA: European Chemicals Agency; EFSA: European Food Safety Authority; ERA: Ecological risk assessment; EU: European Union; FDA: Food and Drug Administration, USA; HELCOM: Baltic Marine Environment Protection Commission (Helsinki commission); ICES: The International Council for the Exploration of the Sea; MP: Microplastic; NGO: Non-governmental Organisation; NP: Nanoplastic; NwS: Norwegian Sea; ONEA: Oceanic North-East Atlantic; OSPAR: Oslo and Paris Commission; PAME: Protection of the Arctic Marine Environment; PFOS: Perfluorooctane sulfonate; POM: Particulate organic matter; POPs: Persistent organic pollutants; UN: United Nations.

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References

1. AMAP. AMAP Assessment 2007: Oil and gas activities in the Arctic - Effects and potential effects. Volume 2. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii + 277 pp. 2010.
2. AMAP. AMAP Assessment 2016: Chemicals of emerging Arctic concern. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xvi + 353 pp. 2017.
3. AMAP. Litter and microplastics. Monitoring plan. 2021.
4. AMAP. Human health in the Arctic 2021. Summary for policy-makers. Tromsø, Norway: Arctic Monitoring and Assessment Programme (AMAP); 2021. p. 16.
5. Andrade H, Glüge J, Herzke D, Ashta NM, Nayagar SM, Scheringer M. Oceanic long-range transport of organic additives present in plastic products: an overview. Environ Sci Eur. 2021;33(1):85.
6. Arctic-Council. Fairbanks Declaration. 2017. p. 16.
7. Backhaus T, Wagner M. Microplastics in the environment: Much ado about nothing? A debate. Global Chall. 2020;4(6):1900022.
8. Ballesteros-Gómez A, Jonkers T, Covaci A, de Boer J. Screening of additives in plastics with high resolution time-of-flight mass spectrometry and different ionization sources: direct probe injection (DIP)-APCI, LC-APCI, and LC-ion booster ESI. Anal Bioanal Chem. 2016;408(11):2945–53.
9. Barbosa F, Adeyemi JA, Bocato MZ, Comas A, Campiglia A. A critical viewpoint on current issues, limitations, and future research needs on micro- and nanoplastic studies: from the detection to the toxicological assessment. Environ Res. 2020;182:109089.
10. Barboza LGA, Lopes C, Oliveira P, Bessa F, Otero V, Henriques B, et al. Microplastics in wild fish from North East Atlantic Ocean and its potential for causing neurotoxic effects, lipid oxidative damage, and human health risks associated with ingestion exposure. Sci Total Environ. 2020;717:134625.
11. Beer S, Garm A, Huwer B, Dierking J, Nielsen TG. No increase in marine microplastic concentration over the last three decades - A case study from the Baltic Sea. Sci Total Environ. 2018;621:1272–9.
12. Beiras R, Schönemann AM. Currently monitored microplastics pose negligible ecological risk to the global ocean. Sci Rep. 2020;10(1):22281.
13. Berezina A, Yakushev E, Savchuk O, Vogelsang C, Staalstrom A. Modelling the influence from biota and organic matter on the transport dynamics of microplastics in the water column and bottom sediments in the Oslo fjord. Water. 2021;13(19):2690.
14. Berge J, Gabrielsen TM, Moline M, Renaud PE. Evolution of the Arctic Calanus complex: an Arctic marine avocado? J Plankton Res. 2012;34(3):191–5.
15. Bergmann M, Lutz B, Tekman MB, Gutow L. Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. Mar Pollut Bull. 2017;125(1):535–40.
16. Bergmann M, Sandhop N, Schewe I, D'Hert D. Observations of floating anthropogenic litter in the Barents Sea and Fram Strait. Arctic Polar Biol. 2016;39(3):553–60.
17. Bergmann M, Wirzberger V, Krumpen T, Lorenz C, Primpke S, Tekman MB, et al. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. Environ Sci Technol. 2017;51(19):11000–10.
18. Besseling E, Redondo-Hasselerharm P, Foekema EM, Koelmans AA. Quantifying ecological risks of aquatic micro- and nanoplastic. Crit Rev Environ Sci Technol. 2019;49(1):32–80.
19. Blindheim J, Østerhus S. The Nordic Seas, Main Oceanographic Features. Washington DC: American Geophysical Union Geophysical Monograph Series; 2005. p. 158.
20. Booth A, Kubowicz S, Beegle-Krause CJ, Skancke J, Nordam T, Landsem E, et al. Microplastic in global and Norwegian marine environments: Distributions, degradation mechanisms and transport. SINTEF Report M-918|2017. 2017.
21. Borrelle SB, Ringma J, Law KL, Monnahan CC, Lebreton L, McGivern A, et al. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science. 2020;369(6510):1515–8.
22. Brandon J, Goldstein M, Ohman MD. Long-term aging and degradation of microplastic particles: Comparing in situ oceanic and experimental weathering patterns. Mar Pollut Bull. 2016;110(1):299–308.
23. Bråte ILN, Eidsvoll DP, Steindal CC, Thomas KV. Plastic ingestion by Atlantic cod (*Gadus morhua*) from the Norwegian coast. Mar Pollut Bull. 2016;112(1–2):105–10.
24. Bråte ILN, Hurley R, Iversen K, Beyer J, Thomas KV, Steindal CC, et al. Mytilus spp. as sentinels for monitoring microplastic pollution in Norwegian coastal waters: a qualitative and quantitative study. Environ Pollut. 2018;243:383–93.
25. Bråte ILN, Hurley R, Lusher A, Buenaventura N, Hultman M, Halsband C, et al. Microplastics in marine bivalves from the Nordic environment. TemaNord report 2020:504. Norway: Nordic Council of Ministers; 2020.
26. Bucci K, Tulio M, Rochman CM. What is known and unknown about the effects of plastic pollution: a meta-analysis and systematic review. Ecol Appl. 2020;30(2):e02044.
27. Butler WE, Guðmundsdóttir LÓ, Logemann K, Langbehn TJ, Marteinsdóttir G. Egg size and density estimates for three gadoids in Icelandic waters and their implications for the vertical distribution of eggs along a stratified water column. J Mar Syst. 2020;204:103290.
28. Caldwell J, Taladriz-Blanco P, Lehner R, Lubskyy A, Ortuso RD, Rothen-Rutishauser B, et al. The micro-, submicron-, and nanoplastic hunt: a review of detection methods for plastic particles. Chemosphere. 2022;293:133514.
29. Cerasa M, Teodori S, Pietrelli L. Searching nanoplastics: From sampling to sample processing. Polymers. 2021;13(21):3658.

30. Chen Q, Gundlach M, Yang S, Jiang J, Velki M, Yin D, et al. Quantitative investigation of the mechanisms of microplastics and nanoplastics toward zebrafish larvae locomotor activity. Sci Total Environ. 2017;584–585:1022–31.
31. Cole M, Lindeque P, Fileman E, Halsband C, Galloway TS. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environ Sci Technol. 2015;49(2):1130–7.
32. Cole M, Lindeque PK, Fileman E, Clark J, Lewis C, Halsband C, et al. Microplastics alter the properties and sinking rates of zooplankton faecal pellets. Environ Sci Technol. 2016;50(6):3239–46.
33. Coppock RL, Galloway TS, Cole M, Fileman ES, Queirós AM, Lindeque PK. Microplastics alter feeding selectivity and faecal density in the copepod, *Calanus helgolandicus*. Sci Total Environ. 2019;687:780–9.
34. Courtene-Jones W, Quinn B, Gary SF, Mogg AOM, Narayanaswamy BE. Microplastic pollution identified in deep-sea water and ingested by benthic invertebrates in the Rockall Trough. North Atlantic Ocean Environ Pollut. 2017;231:271–80.
35. Covernton GA, Pearce CM, Gurney-Smith HJ, Chastain SG, Ross PS, Dower JF, et al. Size and shape matter: a preliminary analysis of microplastic sampling technique in seawater studies with implications for ecological risk assessment. Sci Total Environ. 2019;667:124–32.
36. Cózar A, Echevarría F, González-Gordillo JI, Irigoien X, Úbeda B, Hernández-León S, et al. Plastic debris in the open ocean. Proc Natl Acad Sci. 2014;111(28):10239.
37. Cózar A, Martí E, Duarte CM, García-de-Lomas J, van Sebille E, Ballatore TJ, et al. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation. Sci Adv. 2017;3(4):e1600582.
38. Cunningham EM, Sigwart JD. Environmentally accurate microplastic levels and their absence from exposure studies. Integr Comp Biol. 2019;59(6):1485–96.
39. Cutroneo L, Reboa A, Besio G, Borgogno F, Canesi L, Canuto S, et al. Microplastics in seawater: sampling strategies, laboratory methodologies, and identification techniques applied to port environment. Environ Sci Pollut Res. 2020;27(9):8938–52.
40. Dalpadado P, Arrigo KR, Hjøllo SS, Rey F, Ingvaldsen RB, Sperfeld E, et al. Productivity in the barents sea–response to recent climate variability. PloS One. 2014;9(5):e95273–e95273.
41. Dehnhard N, Herzke D, Gabrielsen GW, Anker-Nilssen T, Ask A, Christensen-Dalsgaard S, et al. Seabirds as indicators of distribution, trends and population level effects of plastics in the Arctic marine environment. Workshop Report. NINA Report 1719. Norway: Norwegian Institute for Nature Research; 2019.
42. Doyle MJ, Watson W, Bowlin NM, Sheavly SB. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Mar Environ Res. 2011;71(1):41–52.
43. ECHA. Annex XV restriction report proposal for a restriction: intentionally added microplastics. 2019.
44. Elmgren R. Understanding human impact on the Baltic ecosystem: changing views in recent decades. Ambio. 2001;30(4–5):222–31.
45. Elmgren R, Blenckner T, Andersson A. Baltic Sea management: Successes and failures. Ambio. 2015;44(Suppl 3):335–44.
46. Enemark J. The Wadden Sea protection and management scheme—towards an integrated coastal management approach? Ocean Coast Manag. 2005;48(11):996–1015.
47. Eriksen E, Skjoldal HR, Gjøsæter H, Primicerio R. Spatial and temporal changes in the Barents Sea pelagic compartment during the recent warming. Prog Oceanogr. 2017;151:206–26.
48. Espinosa C, Esteban M, Cuesta A. Dietary administration of PVC and PE microplastics produces histological damage, oxidative stress and immunoregulation in European sea bass (Dicentrarchus labrax L.). Fish Shellfish Immunol. 2019;95:574–83.
49. Evangeliou N, Grythe H, Klimont Z, Heyes C, Eckhardt S, Lopez-Aparicio S, et al. Atmospheric transport is a major pathway of microplastics to remote regions. Nat Commun. 2020;11(1):3381.
50. Evenset A, Olsson A, Harju M, Gabrielsen G. Settlements on Svalbard as sources for emerging contaminants. Akvaplan-niva report no 7874–1. 2018.
51. Everaert G, Van Cauwenberghe L, De Rijcke M, Koelmans AA, Mees J, Vandegehuchte M, et al. Risk assessment of microplastics in the ocean: modelling approach and first conclusions. Environ Pollut. 2018;242:1930–8.
52. Falk-Andersson J, Tairova Z, Tokvam Drægni T, Larsen HM. Methods for determining the geographical origin and age of beach litter: Challenges and opportunities. Mar Pollut Bull. 2021;172:112901.
53. Fang C, Zheng R, Zhang Y, Hong F, Mu J, Chen M, et al. Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. Chemosphere. 2018;209:298–306.
54. Farrell P, Nelson K. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environ Pollut. 2013;177:1–3.
55. Fauser P, Strand J, Vorkamp K. Risk assessment of added chemicals in plastics in the Danish marine environment. Mar Pollut Bull. 2020;157:111298.
56. Fauser P, Vorkamp K, Strand J. Residual additives in marine microplastics and their risk assessment – A critical review. Mar Pollut Bull. 2022;177:113467.
57. Frank YA, Vorobiev ED, Vorobiev DS, Trifonov AA, Antsiferov DV, Soliman Hunter T, et al. Preliminary screening for microplastic concentrations in the surface water of the Ob and Tom rivers in Siberia, Russia. Sustainability. 2021;13(1):80.
58. Galafassi S, Nizzetto L, Volta P. Plastic sources: a survey across scientific and grey literature for their inventory and relative contribution to microplastics pollution in natural environments, with an emphasis on surface water. Sci Total Environ. 2019;693:133499.
59. GESAMP. Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean Journal Series GESAMP Reports and Studies. 2019. p. 123 (#99).
60. Gjøsæter H. Pelagic fish and the ecological impact of the modern fishing industry in the Barents Sea. Arctic. 1995;48:267–78.
61. Gomiero A, Haave M, Bjorøy Ø, Herzke D, Kögel T, Nikiforov V, et al. Quantification of microplastic in fillet and organs of farmed and wild salmonids- a comparison of methods for detection and quantification. NORCE Miljø research report. 2020.
62. Gouin T. Toward an improved understanding of the ingestion and trophic transfer of microplastic particles: Critical review and implications for future research. Environ Toxicol Chem. 2020;39(6):1119–37.
63. Gouin T, Wania F. Time trends of Arctic contamination in relation to emission history and chemical persistence and partitioning properties. Environ Sci Technol. 2007;41(17):5986–92.
64. Granberg M, von Friesen L, Bach L, Collard F, Strand J, Gabrielsen G. Anthropogenic microlitter in wastewater and marine samples from Ny-Ålesund, Barentsburg and Signehamna, Svalbard. Technical report C-373. Sweden: IVL Swedish Environmental Research Institute; 2019.
65. Granberg M, Winberg von Friesen L, Ask A, Collard F, Magnusson K, Eriksson Wiklund A-K, et al. Microlitter in arctic marine benthic food chains and potential effects on sediment dwelling fauna. TemaNord report 2020:528. Norway: Nordic Council of Ministers; 2020.
66. Granberg ME, Ask A, Gabrielsen GW. Local contamination in Svalbard - Overview and suggestions for remediation actions. Brief report no. 044. Norway: Norwegian polar Institute; 2017.
67. Greven AC, Merk T, Karagöz F, Mohr K, Klapper M, Jovanović B, et al. Polycarbonate and polystyrene nanoplastic particles act as stressors to the innate immune system of fathead minnow (Pimephales promelas). Environ Toxicol Chem. 2016;35(12):3093–100.
68. Grøsvik BE, Prokhorova T, Eriksen E, Krivosheya P, Horneland PA, Prozorkevich D. Assessment of marine litter in the Barents Sea, a part of the joint Norwegian-Russian ecosystem survey. Front Mar Sci. 2018;5:72. https://doi.org/10.3389/fmars.2018.00072.
69. Gunnarsdóttir R, Jenssen PD, Erland Jensen P, Villumsen A, Kallenborn R. A review of wastewater handling in the Arctic with special reference to pharmaceuticals and personal care products (PPCPs) and microbial pollution. Ecol Eng. 2013;50:76–85.
70. Guzzetti E, Sureda A, Tejada S, Faggio C. Microplastic in marine organism: environmental and toxicological effects. Environ Toxicol Pharmacol. 2018;64:164–71.
71. Haegerbaeumer A, Mueller M-T, Fueser H, Traunspurger W. Impacts of micro- and nano-sized plastic particles on benthic invertebrates: a

literature review and gap analysis. Front Environ Sci. 2019;7:17. https://doi.org/10.3389/fenvs.2019.00017.
72. Hahladakis JN, Velis CA, Weber R, Iacovidou E, Purnell P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. J Hazard Mater. 2018;344:179–99.
73. Halsband C, Herzke D. Plastic litter in the European Arctic: What do we know? Emerg Contam. 2019;5:308–18.
74. Hamilton B, Jantunen L, Bergmann M, Vorkamp K, Aherne J, Magnusson K, et al. Monitoring microplastics in the atmosphere and cryosphere in the circumpolar North: a case for multi-compartment monitoring. Arct Sci. 2021. https://doi.org/10.1139/as-2021-0054.
75. Hänninen J, Weckström M, Pawłowska J, Szymańska N, Uurasjärvi E, Zajaczkowski M, et al. Plastic debris composition and concentration in the Arctic Ocean, the North Sea and the Baltic Sea. Mar Pollut Bull. 2021;165:112150.
76. Hardesty BD, Harari J, Isobe A, Lebreton L, Maximenko N, Potemra J, et al. Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. Front Mar Sci. 2017;4:30. https://doi.org/10.3389/fmars.2017.00030.
77. Harris PT. The fate of microplastic in marine sedimentary environments: a review and synthesis. Mar Pollut Bull. 2020;158:111398.
78. HELCOM. State of the Baltic Sea – Second HELCOM holistic assessment 2011–2016. Baltic Sea Environment Proceedings 155. 2018.
79. Herzke D, Ghaffari PN, Sundet JH, Tranang CA, Halsband C. Microfiber emissions from wastewater effluents: abundance, transport behavior and exposure risk for biota in an arctic fjord. Front Environ Sci. 2021. https://doi.org/10.3389/fenvs.2021.662168.
80. Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol. 2012;46(6):3060–75.
81. Huiskes AHL, Rozema J. The impact of anthropogenic activities on the coastal wetlands of the North Sea. In: Salomons W, Bayne BL, Duursma EK, Förstner U, editors. Pollution of the North Sea. Springer, Berlin: Heidelberg; 1988. p. 455–73.
82. Humphries S. Filter feeders and plankton increase particle encounter rates through flow regime control. Proc Natl Acad Sci. 2009;106(19):7882.
83. Huntington A, Corcoran PL, Jantunen L, Thaysen C, Bernstein S, Stern GA, et al. A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding eastern Canadian Arctic waters of Nunavut. Facets. 2020;5(1):432–54.
84. Huserbråten MBO, Hattermann T, Broms C, Albretsen J. Trans-polar drift-pathways of riverine European microplastic. Sci Rep. 2022;12(1):3016.
85. ICES. The Barents Sea and the Norwegian Sea. In: ICES Advice 2009, Book 3. International Council for the Exploration of the Sea. 2009.
86. ICES. Barents Sea Ecoregion. In: ICES Ecosystem Overviews. International Council for the Exploration of the Sea. 2019. Published 12 Dec.
87. ICES. Norwegian Sea Ecoregion. In: ICES Ecosystem Overviews. International Council for the Exploration of the Sea. 2019. Published 12 Dec.
88. ICES. Oceanic Northeast Atlantic ecoregion. In: ICES Ecosystem Overviews. International Council for the Exploration of the Sea. 2019. Published 12 Dec.
89. ICES. Baltic Sea Ecoregion. In: ICES Ecosystem Overviews. International Council for the Exploration of the Sea. 2020. Published 10 Dec.
90. ICES. Greater North Sea Ecoregion. In: ICES Ecosystem Overviews. International Council for the Exploration of the Sea. 2020. Published 10 Dec.
91. ICES. Greenland Sea ecoregion. In: ICES Ecosystem Overviews. International Council for the Exploration of the Sea. 2020. Published 10 Dec.
92. ICES. Icelandic Waters Ecoregion. In: ICES Ecosystem Overviews. International Council for the Exploration of the Sea. 2020. Published 10 Dec.
93. IMR. Institute of Marine Research. Map "Atlantic_Circulation". http://maps.imr.no/geoserver/web/. 2022.
94. Isobe A, Kubo K, Tamura Y, Kako Si, Nakashima E, Fujii N. Selective transport of microplastics and mesoplastics by drifting in coastal waters. Mar Pollut Bull. 2014;89(1):324–30.
95. Jang M, Shim WJ, Cho Y, Han GM, Song YK, Hong SH. A close relationship between microplastic contamination and coastal area use pattern. Water Res. 2020;171:115400.
96. Jiang Y, Yang F, Zhao YA, Wang J. Greenland Sea Gyre increases microplastic pollution in the surface waters of the Nordic Seas. Sci Total Environ. 2020;712:9.
97. Johannesen E, Ingvaldsen RB, Bogstad B, Dalpadado P, Eriksen E, Gjøsæter H, et al. Changes in Barents Sea ecosystem state, 1970–2009: climate fluctuations, human impact, and trophic interactions. ICES J Mar Sci. 2012;69(5):880–9.
98. Johnsen T, Nygaard K, Olsgard F. Biogeographical regions in Europe: the North-east Atlantic Ocean - huge, deep and heavily exploited. In: Europe's biodiversity - biogeographical regions and seas. Norway: European Environment Agency; 2008.
99. Jonsson P. Sediment Burial of PCBs in the Offshore Baltic Sea. Ambio. 2009;29:260–7.
100. Jonsson S, Valdimarsson H. The flow of Atlantic water to the North Icelandic Shelf and its relation to the drift of cod larvae. ICES J Mar Sci. 2005;62:1350–9.
101. Kane IA, Clare MA, Miramontes E, Wogelius R, Rothwell JJ, Garreau P, et al. Seafloor microplastic hotspots controlled by deep-sea circulation. Sci. 2020;368(6495):1140.
102. Kanhai LDK, Gardfeldt K, Krumpen T, Thompson RC, O'Connor I. Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. Sci Rep. 2020;10(1):5004.
103. Kanhai LDK, Gårdfeldt K, Lyashevska O, Hassellöv M, Thompson RC, O'Connor I. Microplastics in sub-surface waters of the Arctic Central Basin. Mar Pollut Bull. 2018;130:8–18.
104. Kanhai LDK, Officer R, Lyashevska O, Thompson RC, O'Connor I. Microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean. Mar Pollut Bull. 2017;115(1):307–14.
105. Kanwischer M, Asker N, Wernersson AS, Wirth MA, Fisch K, Dahlgren E, et al. Substances of emerging concern in Baltic Sea water: Review on methodological advances for the environmental assessment and proposal for future monitoring. Ambio. 2022;51(6):1588–608.
106. Koelmans AA, Besseling E, Foekema E, Kooi M, Mintenig S, Ossendorp BC, et al. Risks of plastic debris: unravelling fact, opinion, perception, and belief. Environ Sci Technol. 2017;51(20):11513–9.
107. Kühn S, Schaafsma FL, van Werven B, Flores H, Bergmann M, Egelkraut-Holtus M, et al. Plastic ingestion by juvenile polar cod (Boreogadus saida) in the Arctic Ocean. Polar Biol. 2018;41(6):1269–78.
108. Kwadijk J, Arnell NW, Mudersbach C, de Weerd M, Kroon A, Quante M. Recent change—River flow. In: Quante M, Colijn F, editors. North Sea region climate change assessment. Cham: Springer International Publishing; 2016. p. 137–46.
109. Kylin H. Marine debris on two Arctic beaches in the Russian Far East. Polar Res. 2020;39. https://doi.org/10.33265/polar.v39.3381.
110. Kögel T, Bjorøy Ø, Toto B, Bienfait AM, Sanden M. Micro- and nanoplastic toxicity on aquatic life: determining factors. Sci Total Environ. 2020;709:136050.
111. Lassen C, Hansen SF, Magnusson K, Hartmann NB, Rehne Jensen P, Nielsen TG, et al. Microplastics: occurrence, effects and sources of releases to the environment in Denmark. Denmark: Danish Environmental Protection Agency; 2015.
112. Latarius K, Quadfasel D. Water mass transformation in the deep basins of the Nordic Seas: Analyses of heat and freshwater budgets. Deep Sea Res Part I Oceanogr Res Pap. 2016;114:23–42.
113. Law K, Morét S, Goodwin D, Zettler E, Deforce E, Kukulka T, et al. Distribution of surface plastic debris in the Eastern Pacific Ocean from an 11-Year data set. Environ Sci Technol. 2014;48:4732–8.
114. Lebreton LCM, van der Zwet J, Damsteeg J-W, Slat B, Andrady A, Reisser J. River plastic emissions to the world's oceans. Nat Commun. 2017;8(1):15611.
115. Leppäranta M, Myrberg K. Physical oceanography of the Baltic Sea. Berlin: Springer, Heidelberg; 2009.
116. Lespes G, Faucher S, Slaveykova VI. Natural nanoparticles, anthropogenic nanoparticles, where is the frontier? Front Environ Sci. 2020;8(71). https://doi.org/10.3389/fenvs.2020.00071.
117. Li J, Lusher AL, Rotchell JM, Deudero S, Turra A, Bråte ILN, et al. Using mussel as a global bioindicator of coastal microplastic pollution. Environ Pollut. 2019;244:522–33.
118. Li YF, Macdonald RW, Jantunen LMM, Harner T, Bidleman TF, Strachan WMJ. The transport of β-hexachlorocyclohexane to the western Arctic Ocean: a contrast to α-HCH. Sci Total Environ. 2002;291(1):229–46.

119. Lien VS, Trofimov AG. Formation of Barents Sea branch water in the north-eastern Barents Sea. Polar Res. 2013;32(1):18905.
120. Lima ARA, Ferreira GVB, Barrows APW, Christiansen KS, Treinish G, Toshack MC. Global patterns for the spatial distribution of floating microfibers: Arctic Ocean as a potential accumulation zone. J Hazard Mater. 2021;403:123796.
121. Lithner D, Larsson Å, Dave G. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Sci Total Environ. 2011;409(18):3309–24.
122. Lobelle D, Kooi M, Koelmans AA, Laufkötter C, Jongedijk CE, Kehl C, et al. Global modeled sinking characteristics of biofouled microplastic. J Geophys Res Oceans. 2021;126(4):e2020JC017098.
123. Logemann K, Ólafsson J, Snorrason Á, Valdimarsson H, Marteinsdóttir G. The circulation of Icelandic waters – a modelling study. Ocean Sci. 2013;9(5):931–55.
124. Loughlin C, Marques Mendes AR, Morrison L, Morley A. The role of oceanographic processes and sedimentological settings on the deposition of microplastics in marine sediment: Icelandic waters. Mar Pollut Bull. 2021;164:111976.
125. Lusher A, Pettersen R. Sea-based sources of microplastics to the Norwegian marine environment. NIVA report 7568. Norway: Norwegian Environment Agency M-1911; 2021.
126. Lusher AL, Burke A, O'Connor I, Officer R. Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. Mar Pollut Bull. 2014;88(1–2):325–33.
127. Lusher AL, Hernandez-Milian G, O'Brien J, Berrow S, O'Connor I, Officer R. Microplastic and macroplastic ingestion by a deep diving, oceanic cetacean: The True's beaked whale Mesoplodon mirus. Environ Pollut. 2015;199:185–91.
128. Lusher AL, Hurley R, Arp HPH, Booth AM, Bråte ILN, Gabrielsen GW, et al. Moving forward in microplastic research: A Norwegian perspective. Environ Int. 2021;157:106794.
129. Lusher AL, McHugh M, Thompson RC. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar Pollut Bull. 2013;67(1):94–9.
130. Macdonald RW, Barrie LA, Bidleman TF, Diamond ML, Gregor DJ, Semkin RG, et al. Contaminants in the Canadian Arctic: 5 years of progress in understanding sources, occurrence and pathways. Sci Total Environ. 2000;254(2):93–234.
131. MacKnight SD. Selection of bottom sediment sampling stations. In: Mudroch A, MacKnight SD, editors. Handbook of techniques for aquatic sediments sampling. Boca Raton: CRC Press; 1994. p. 17–28.
132. Magnusson K, Jörundsdóttir H, Norén F, Lloyd H, Talvitie J, Setälä O. Microlitter in sewage treatment systems: a Nordic perspective on waste water treatment plants as pathways for microscopic anthropogenic particles to marine systems. TemaNord report 2016:510. Norway: Nordic Council of Ministers; 2016.
133. Mani T, Hauk A, Walter U, Burkhardt-Holm P. Microplastics profile along the Rhine River. Sci Rep. 2015;5(1):17988.
134. Markic A, Gaertner J-C, Gaertner-Mazouni N, Koelmans AA. Plastic ingestion by marine fish in the wild. Crit Rev Environ Sci Technol. 2020;50(7):657–97.
135. Martin J, Granberg M, Provencher JF, Liborion M, Pijogge L, Magnusson K, et al. The power of multi-matrix monitoring in the Pan-Arctic region: plastics in water and sediment. Arct Sci. 2021. https://doi.org/10.1139/AS-2021-0056.
136. Mauritzen C, Hansen E, Andersson M, Berx B, Beszczynska-Möller A, Burud I, et al. Closing the loop – Approaches to monitoring the state of the Arctic Mediterranean during the International Polar Year 2007–2008. Prog Oceanogr. 2011;90(1):62–89.
137. Miller ME, Hamann M, Kroon FJ. Bioaccumulation and biomagnification of microplastics in marine organisms: a review and meta-analysis of current data. PLoS One. 2020;15(10):e0240792.
138. Mountford AS, Morales Maqueda MA. Modeling the accumulation and transport of microplastics by sea ice. J Geophys Res Oceans. 2021;126(2):e2020JC016826.
139. MSFD. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). 2017.
140. Møskeland T, Knutsen H, Arp H, Lilleeng Ø, Pettersen A. Microplastics in sediments on the Norwegian Continental Shelf. Miljødirektoratet report M-976. Norway: Norwegian Environment Agency; 2018.
141. Nelms SE, Galloway TS, Godley BJ, Jarvis DS, Lindeque PK. Investigating microplastic trophic transfer in marine top predators. Environ Poll. 2018;238:999–1007.
142. Obbard R, Sadri S, Wong YQ, Khitun AA, Baker I, Thompson RC. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earths Future. 2014;2(6):315–20.
143. Obbard RW. Microplastics in polar regions: The role of long range transport. Curr Opin Environ Sci Health. 2018;1:24–9.
144. Ogonowski M, Wenman V, Barth A, Hamacher-Barth E, Danielsson S, Gorokhova E. Microplastic intake, its biotic drivers, and hydrophobic organic contaminant levels in the Baltic herring. Front Environ Sci. 2019;7:134.
145. Ortuño Montesinos R. Eficacia fagocítica en hemocitos de mejillón: efectos del mercurio en presencia de microplásticos extracelulares. Universidad Católica de Valencia. Degree Final Project. http://hdl.handle.net/20.500.12466/40. 2019.
146. OSPAR. Greater North Sea. In: OSPAR quality status report 2000. London: OSPAR Commission; 2000.
147. OSPAR. The North East Atlantic. In: OSPAR quality status report 2010. London: OSPAR Commission; 2010.
148. PAME. Desktop study on marine litter including microplastics in the Arctic. 2019.
149. Pannetier P, Morin B, Le Bihanic F, Dubreil L, Clérandeau C, Chouvellon F, et al. Environmental samples of microplastics induce significant toxic effects in fish larvae. Environ Int. 2020;134:105047.
150. Peeken I, Primpke S, Beyer B, Gütermann J, Katlein C, Krumpen T, et al. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat Commun. 2018;9(1):1505.
151. Peng L, Fu D, Qi H, Lan CQ, Yu H, Ge C. Micro- and nano-plastics in marine environment: Source, distribution and threats — A review. Sci Total Environ. 2020;698:134254.
152. Pickart RS, Spall MA, Torres DJ, Våge K, Valdimarsson H, Nobre C, et al. The North Icelandic jet and its relationship to the North Icelandic Irminger current. J Mar Res. 2017;75(5):605–39.
153. Polasek L, Bering J, Kim H, Neitlich P, Pister B, Terwilliger M, et al. Marine debris in five national parks in Alaska. Mar Pollut Bull. 2017;117(1–2):371–9.
154. Poon FE, Provencher JF, Mallory ML, Braune BM, Smith PA. Levels of ingested debris vary across species in Canadian Arctic seabirds. Mar Pollut Bull. 2017;116(1):517–20.
155. Ray GC, McCormick-Ray J. Coastal-marine conservation: Science and policy. Hoboken: Wiley-Blackwell; 2003.
156. Rebesco M, Hernández-Molina FJ, Van Rooij D, Wåhlin A. Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. Mar Geol. 2014;352:111–54.
157. Rehberger K, Werner I, Hitzfeld B, Segner H, Baumann L. 20 Years of fish immunotoxicology – what we know and where we are. Crit Rev Toxicol. 2017;47(6):516–42.
158. Ribeiro F, Okoffo ED, O'Brien JW, Fraissinet-Tachet S, O'Brien S, Gallen M, et al. Quantitative analysis of selected plastics in high-commercial-value Australian seafood by pyrolysis Gas Chromatography Mass Spectrometry. Environ Sci Technol. 2020;54(15):9408–17.
159. Ross P, Chastain S, Vassilenko E, Etemadifar A, Zimmermann S, Quesnel S-A, et al. Pervasive distribution of polyester fibres in the Arctic Ocean is driven by Atlantic inputs. Nat Commun. 2021;12(1):106.
160. Routti H, Harju M, Lühmann K, Aars J, Ask A, Goksøyr A, et al. Concentrations and endocrine disruptive potential of phthalates in marine mammals from the Norwegian Arctic. Environ Int. 2021;152:106458.
161. Rummel CD, Löder MGJ, Fricke NF, Lang T, Griebeler E-M, Janke M, et al. Plastic ingestion by pelagic and demersal fish from the North Sea and Baltic Sea. Mar Pollut Bull. 2016;102(1):134–41.
162. Rydningen TA, Høgseth GV, Lasabuda APE, Laberg JS, Safronova PA, Forwick M. An early neogene—Early quaternary contourite drift system on the SW Barents Sea continental margin, Norwegian Arctic. Geochem Geophys Geosystems. 2020;21(11):20.
163. Salomons W, Bayne BL, Duursma EK, Förstner U. Pollution of the North Sea - An assessment. Berlin Heidelberg: Springer-Verlag; 1988.

164. Scherer C, Weber A, Stock F, Vurusic S, Egerci H, Kochleus C, et al. Comparative assessment of microplastics in water and sediment of a large European river. Sci Total Environ. 2020;738:139866.
165. Schernewski G, Radtke H, Hauk R, Baresel C, Olshammar M, Oberbeckmann S. Urban microplastics emissions: Effectiveness of retention measures and consequences for the Baltic Sea. Front Mar Sci. 2021;8. https://doi.org/10.3389/fmars.2021.594415.
166. Schernewski G, Radtke H, Hauk R, Baresel C, Olshammar M, Osinski R, et al. Transport and behavior of microplastics emissions from urban sources in the Baltic Sea. Front Environ Sci. 2020;8:579361.
167. Setälä O, Magnusson K, Lehtiniemi M, Norén F. Distribution and abundance of surface water microlitter in the Baltic Sea: a comparison of two sampling methods. Mar Pollut Bull. 2016;110(1):177–83.
168. Sigurðsson V, Halldórsson P. Örplast í hafinu við Ísland: Helstu uppspretttur, magn og farvegir í umhverfinu (Report in Icelandic). Biopol ehf. and NNV nature and research center. https://harkanatta.github.io/orplastskyrslaUAR/. 2019.
169. Solomando A, Capó X, Alomar C, Álvarez E, Compa M, Valencia JM, et al. Long-term exposure to microplastics induces oxidative stress and a pro-inflammatory response in the gut of *Sparus aurata* Linnaeus, 1758. Environ Pollut. 2020;266:115295.
170. Strand J, Tairova Z, Danielsen J, Hansen JW, Magnusson K, Naustvoll LJ, et al. Marine litter in Nordic waters. TemaNord report 2015:521. Norway: Nordic Council of Ministers; 2015.
171. Strand KO, Huserbråten M, Dagestad K-F, Mauritzen C, Grøsvik BE, Nogueira LA, et al. Potential sources of marine plastic from survey beaches in the Arctic and Northeast Atlantic. Sci Total Environ. 2021;790:148009.
172. Sundt P, Rønnekleiv S, Thomas Rem H, Schulze PE. Norske landbaserte kilder til mikroplast. Miljødirektoratet report M-1910 (report in Norwegian). Norway: Norwegian Environment Agency; 2020.
173. Suthers IM, Bwoling L, Kobayashi T, Rissik D. Sampling methods for plankton. In: Suthers I, Rissik D, Richardson A, editors. Plankton - A guide to their ecology and monitoring for water quality. 2nd ed. Boca Raton: CRC Press; 2019. p. 63–90.
174. Tamminga M, Stoewer S-C, Fischer EK. On the representativeness of pump water samples versus manta sampling in microplastic analysis. Environ Pollut. 2019;254:112970.
175. Tanaka K, van Franeker JA, Deguchi T, Takada H. Piece-by-piece analysis of additives and manufacturing byproducts in plastics ingested by seabirds: Implication for risk of exposure to seabirds. Mar Pollut Bull. 2019;145:36–41.
176. Tekman MB, Wekerle C, Lorenz C, Primpke S, Hasemann C, Gerdts G, et al. Tying up loose ends of microplastic pollution in the Arctic: Distribution from the sea surface through the water column to deep-sea sediments at the HAUSGARTEN observatory. Environ Sci Technol. 2020;54(7):4079–90.
177. Tošić TN, Vruggink M, Vesman A. Microplastics quantification in surface waters of the Barents, Kara and White Seas. Mar Pollut Bull. 2020;161:111745.
178. UNEP. Stockholm Convention on Persistent Organic Pollutants (POPs). Text and Annexes, revised in 2017. Sweden: United Nations Environment Programme; 2018.
179. UNEP. Proposal to list UV-328 in Annex A to the Stockholm Convention on Persistent Organic Pollutants. Persistent Organic Pollutants Review Committee, 16th meeting, Geneva (online), 11–16 January 2021. 2021.
180. van Sebille E, Aliani S, Law KL, Maximenko N, Alsina JM, Bagaev A, et al. The physical oceanography of the transport of floating marine debris. Environ Res Lett. 2020;15(2):023003.
181. van Sebille E, England MH, Froyland G. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environ Res Lett. 2012;7(4):044040.
182. van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty BD, van Franeker JA, et al. A global inventory of small floating plastic debris. Environ Res Lett. 2015;10(12):124006.
183. Vesman A, Moulin E, Egorova A, Zaikov K. Marine litter pollution on the Northern Island of the Novaya Zemlya archipelago. Mar Pollut Bull. 2020;150:110671.
184. Vihtakari M. ggOceanMaps: Plot Data on Oceanographic Maps using 'ggplot2' - R package version 1.2.6. https://mikkovihtakari.github.io/ggOceanMaps/. 2022.
185. Vogel S. Life in moving fluids: the physical biology of flow - revised and expanded second edition. USA: Princeton University Press; 2020.
186. von Friesen LW, Granberg ME, Pavlova O, Magnusson K, Hassellöv M, Gabrielsen GW. Summer sea ice melt and wastewater are important local sources of microlitter to Svalbard waters. Environ Int. 2020;139:105511.
187. Vorkamp K, Falk K, Møller S, Rigét FF, Sørensen PB. Regulated and unregulated halogenated flame retardants in Peregrine Falcon eggs from Greenland. Environ Sci Technol. 2018;52(2):474–83.
188. Vroom RJE, Koelmans AA, Besseling E, Halsband C. Aging of microplastics promotes their ingestion by marine zooplankton. Environ Pollut. 2017;231:987–96.
189. Waldschläger K, Lechthaler S, Stauch G, Schüttrumpf H. The way of microplastic through the environment - Application of the source-pathway-receptor model (review). Sci Total Environ. 2020;713:136584.
190. Wania F, Mackay D. Global Fractionation and Cold Condensation of Low Volatility Organochlorine Compounds in Polar Regions. Ambio. 1993;22(1):10–8.
191. Ward JE, Zhao S, Holohan BA, Mladinich KM, Griffin TW, Wozniak J, et al. Selective ingestion and egestion of plastic Particles by the blue mussel (*Mytilus edulis*) and Eastern oyster (*Crassostrea virginica*): Implications for using bivalves as bioindicators of microplastic pollution. Environ Sci Technol. 2019;53(15):8776–84.
192. Weber JEH, Ghaffari P. Wave-induced Lagrangian drift in a porous seabed. Environ Fluid Mech. 2021. https://doi.org/10.1007/s10652-021-09823-4.
193. Woodall LC, Sanchez-Vidal A, Canals M, Paterson GL, Coppock R, Sleight V, et al. The deep sea is a major sink for microplastic debris. R Soc Open Sci. 2014;1(4):140317.
194. Woods MN, Stack ME, Fields DM, Shaw SD, Matrai PA. Microplastic fiber uptake, ingestion, and egestion rates in the blue mussel (*Mytilus edulis*). Mar Pollut Bull. 2018;137:638–45.
195. Wu P, Huang J, Zheng Y, Yang Y, Zhang Y, He F, et al. Environmental occurrences, fate, and impacts of microplastics. Ecotoxicol Environ Saf. 2019;184:109612.
196. Xia X, Sun M, Zhou M, Chang Z, Li L. Polyvinyl chloride microplastics induce growth inhibition and oxidative stress in *Cyprinus carpio* var. larvae. Sci Total Environ. 2020;716:136479.
197. Yakushev E, Gebruk A, Osadchiev A, Pakhomova S, Lusher A, Berezina A, et al. Microplastics distribution in the Eurasian Arctic is affected by Atlantic waters and Siberian rivers. Commun Earth Environ. 2021;2(1):23.
198. Yang X, Wang H, Zhang L, Kong L, Chen Y, He Q, et al. Marine algae facilitate transfer of microplastics and associated pollutants into food webs. Sci Total Environ. 2021;787:147535.
199. Zhao Z, Xie Z, Möller A, Sturm R, Tang J, Zhang G, et al. Distribution and long-range transport of polyfluoroalkyl substances in the Arctic, Atlantic Ocean and Antarctic coast. Environ Pollut. 2012;170:71–7.

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