Environment International 157 (2021) 106794

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Moving forward in microplastic research: A Norwegian perspective

Amy L. Lusher [a,b,*], Rachel Hurley [a], Hans Peter H. Arp [c,d], Andy M. Booth [e], Inger Lise N. Bråte [a], Geir W. Gabrielsen [f], Alessio Gomiero [g], Tânia Gomes [a], Bjørn Einar Grøsvik [h], Norman Green [a], Marte Haave [g,i], Ingeborg G. Hallanger [f], Claudia Halsband [j], Dorte Herzke [k,l], Erik J. Joner [m], Tanja Kögel [b,h], Kirsten Rakkestad [n], Sissel B. Ranneklev [a], Martin Wagner [o], Marianne Olsen [a]

[a] *Norwegian Institute for Water Research (NIVA), Gaustadalléen 21, NO-0349 Oslo, Norway*
[b] *Department of Biological Sciences, University of Bergen, NO-5020 Bergen, Norway*
[c] *Norwegian Geotechnical Institute (NGI), P.O. Box 3930 Ullevål Stadion, NO-0806 Oslo, Norway*
[d] *Department of Chemistry, Norwegian University of Science and Technology (NTNU), Høgskoleringen 5, NO-7491 Trondheim, Norway*
[e] *SINTEF Ocean, Brattørkaia 17 C, NO-7010 Trondheim, Norway*
[f] *Norwegian Polar Institute (NPI), Fram Centre, NO-9296 Tromsø, Norway*
[g] *Norwegian Research Center (NORCE), Nygårdsporten 112, NO-5008 Bergen, Norway*
[h] *Institute of Marine Research (IMR), P.O. Box 1870 Nordnes, NO-5817 Bergen, Norway*
[i] *Department of Chemistry, University of Bergen, Allegaten 41, NO-5007 Bergen, Norway*
[j] *Akvaplan-niva, Fram Centre, NO-9296 Tromsø, Norway*
[k] *Norwegian Institute for Air Research (NILU), Fram Centre, NO-9296 Tromsø, Norway*
[l] *Institute for Arctic and Marine Biology, UiT The Arctic University of Norway, N-9037 Tromsø, Norway*
[m] *Norwegian Institute for Bioeconomy Research (NIBIO), Høyskoleveien 7, NO-1431 Ås, Norway*
[n] *The Norwegian Scientific Committee for Food and Environment (VKM), P.O. Box 222 Skøyen, NO-0213 Oslo, Norway*
[o] *Department of Biology, Norwegian University of Science and Technology (NTNU), Høgskoleringen 5, NO-7491 Trondheim, Norway*

ARTICLE INFO

Handling Editor: Olga-Ioanna Kalantzi

Keywords:
Microplastic
Nanoplastic
Plastic
Monitoring
Sources
Risk assessment

ABSTRACT

Given the increasing attention on the occurrence of microplastics in the environment, and the potential environmental threats they pose, there is a need for researchers to move quickly from basic understanding to applied science that supports decision makers in finding feasible mitigation measures and solutions. At the same time, they must provide sufficient, accurate and clear information to the media, public and other relevant groups (e.g., NGOs). Key requirements include systematic and coordinated research efforts to enable evidence-based decision making and to develop efficient policy measures on all scales (national, regional and global). To achieve this, collaboration between key actors is essential and should include researchers from multiple disciplines, policy-makers, authorities, civil and industry organizations, and the public. This further requires clear and informative communication processes, and open and continuous dialogues between all actors. Cross-discipline dialogues between researchers should focus on scientific quality and harmonization, defining and accurately communicating the state of knowledge, and prioritization of topics that are critical for both research and policy, with the common goal to establish and update action plans for holistic benefit. In Norway, cross-sectoral collaboration has been fundamental in supporting the national strategy to address plastic pollution. Researchers, stakeholders and the environmental authorities have come together to exchange knowledge, identify knowledge gaps, and set targeted and feasible measures to tackle one of the most challenging aspects of plastic pollution: microplastic. In this article, we present a Norwegian perspective on the state of knowledge on microplastic research efforts. Norway's involvement in international efforts to combat plastic pollution aims at serving as an example of how key actors can collaborate synergistically to share knowledge, address shortcomings, and outline ways forward to address environmental challenges.

---

* Corresponding author.
E-mail address: amy.lusher@niva.no (A.L. Lusher).

https://doi.org/10.1016/j.envint.2021.106794
Received 22 March 2021; Received in revised form 21 July 2021; Accepted 22 July 2021

1. Introduction

Finding effective and viable solutions to emerging and complex environmental challenges requires open dialogue supported by efficient sharing of high-quality scientific data. In recent years, there has been a significant increase in global attention on the emerging environmental problems related to plastic pollution (Qin et al., 2020; SAPEA, 2019). This attention has been the result of the public and media response to perceived impacts. We are now facing an unprecedented global political will to find solutions to reduce plastic pollution and to develop regulatory initiatives at national and international levels. Driven by public opinion and political demand for evidence, and scientific interest and competition, research on plastic pollution has been fast-paced (Zhang et al., 2020). Despite over a decade of attention and a substantial volume of work, our understanding of the impacts and risk associated with plastic pollution remains in its infancy. This is partly underpinned by a lack of standardized, harmonized, or fully validated methods for capturing the full scale of plastic pollution and assessing its environmental and societal impacts, particularly regarding the smallest plastic particles.

To enable robust risk assessment, more knowledge on the environmental occurrence, fate, and impacts of plastic is required across the full continuum of particle sizes and types. Similarly, there is a need for greater understanding of their sources and transport mechanisms to facilitate effective mitigation measures (SAPEA, 2019; VKM, 2019). Scientific outputs must be integrated into the development of policies and measures, but the current needs for rapid and reliable progress challenges the limits of traditional scientific processes and established procedures for publication and communicating knowledge. Multiple new platforms and tools (e.g., social media, webinars) are available for communicating and sharing information to a wide range of stakeholder groups including the public, meaning new knowledge is now distributed faster and more openly than ever before, and to an audience extending beyond that of the scientific community. However, many of these new communication channels lack any form of independent peer-review or quality assurance processes. This results in information of varying quality being made freely available, often to end users without the skills to evaluate its value (e.g., media/public). At the same time, it is important that policy and decision makers have accelerated access to robust and simplified information. This leads to an increased need for actively navigating and digesting the densely populated outputs to find appropriate and high-quality information for development into policies and regulations. Specifically, better communication of science is essential within this research field.

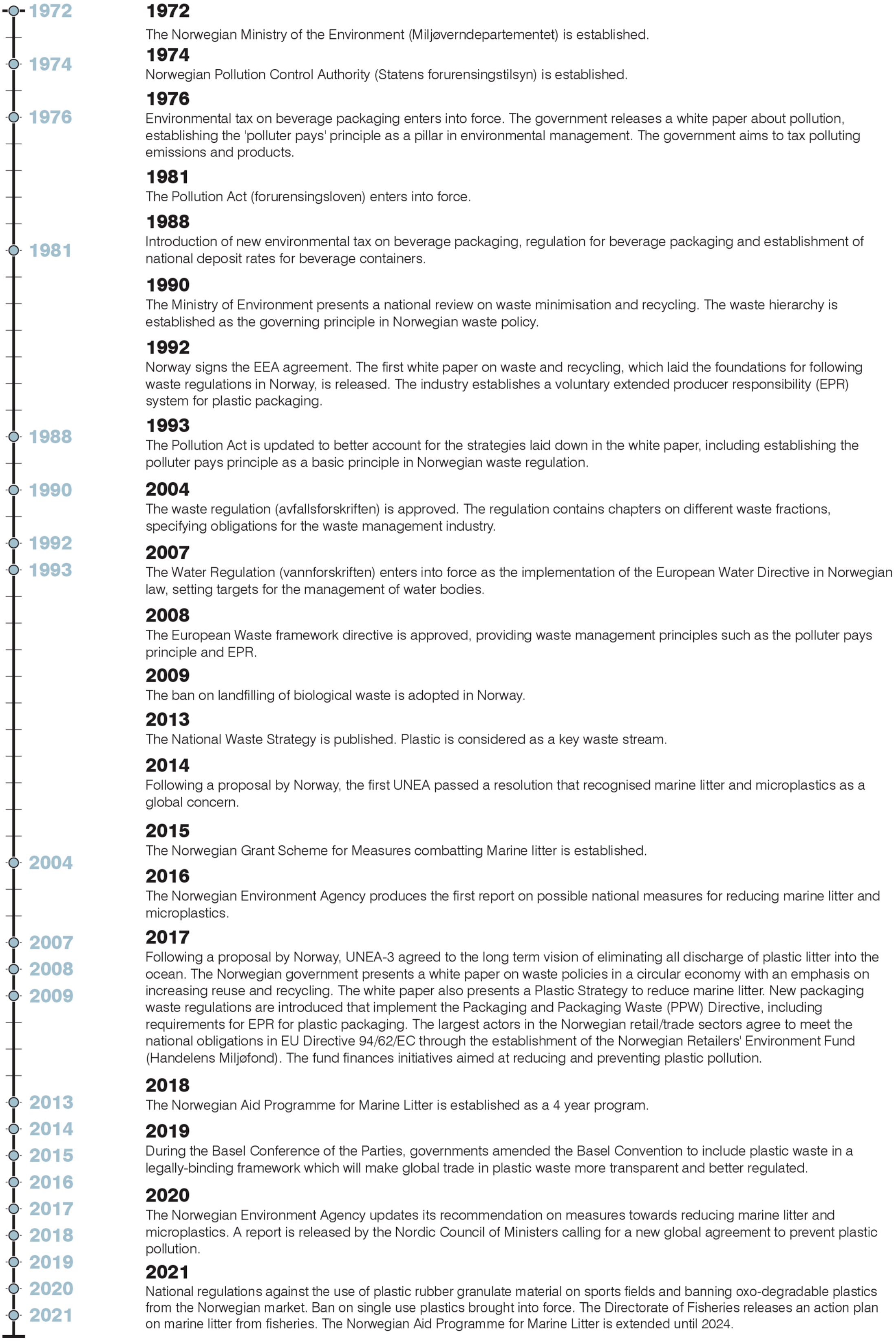
Norway has a long history of implementing legislation related to environmental protection and waste management (Fig. 1). With Europe's longest coastline and an economy driven by its marine environment and ocean-based resources, sustainable coastal management is fundamental to Norway's future. Historically, Norway has taken an active stance to ensure clean and healthy seas, both locally and internationally, by implementing and enforcing domestic and international legislation, helping to focus global attention on maritime issues, and participating actively in joint international efforts. More recently, this has included a strong focus on national and international initiatives to address plastic pollution (Fig. 1). For example, in 2014, Norway presented a proposal to the UN Environment Assembly (UNEA) to enshrine marine litter and microplastic into a resolution of the UN Environment Program (UNEP; UNEP/EA.1/Res.6). This was extended by another proposal from Norway in 2017 for a long-term vision to eliminate all plastic discharges to the oceans by the third UNEA (UNEP/EA.3/RES.7). At the 2019 UNEA meeting, the Norwegian Minister of Environment proposed a new global agreement combatting marine litter, to which several nations have already given their support. Nationally, two action plans targeting marine litter and microplastic were developed in 2016, setting out road maps for future national focus. In 2018, the Prime Minister of Norway instigated a major Intergovernmental Panel on the New Ocean Economy and committed 1.6 billion Norwegian kroner, NOK (~160 million Euro) to a new development aid program on marine litter and microplastic (Regjeringen, 2020). Running from 2019 to 2024, the aid program will help to achieve UN Sustainability Goal 14.1, where the world's governments aim to prevent and significantly reduce all forms of marine pollution by 2025. A proportion of these aid funded projects - which specifically focus on building capacity in the Global South - include natural and social science methods to monitor and mitigate the effects of plastic waste on the local, regional, and global environment. Norway has also been active in identifying knowledge gaps and drafting strategies to tackle plastic pollution in the Arctic, as the host of the Arctic Monitoring and Assessment Plan (AMAP) office and participating in the Protection of the Arctic Marine Environment Working Group (PAME) of the Arctic Council.

Early recognition of the potential issues associated with (micro) plastic pollution by governing bodies in Norway, and a prompt allocation of resources, was critical in opening up opportunities for research, which has contributed to positioning Norway amongst the nations at the forefront of global plastics research. Together with the Research Council of Norway (RCN), Norwegian authorities have stimulated research into plastic and microplastic pollution by providing financial support for national and international research since 2013. Norwegian researchers have now established a strong track record of research. Norwegian institutes have been partners in over 80 national or international research projects related to plastic or microplastic (Table S1). This does not include additional assessment projects funded by the Norwegian Environment Agency (NEA) or the Nordic Council of Ministers. The total budgets of the research projects equate to ~ 751 million NOK (~61 million Euro) from national funding sources and close to 62.6 million Euros from European funding initiatives such as the European Commission H2020 and JPI Oceans programs (Table S1). These projects address a diverse range of topics, including environmental monitoring, analytical method development, environmental fate, ecotoxicology and risk assessment, environmental modelling, and solutions to reduce pollution. They also reveal a greater research focus on microplastic than macroplastic, which mirrors the global research trend.

Norwegian environment authorities have taken an active role in seeking information and knowledge on the potential risks of plastics by establishing an open dialogue with researchers working in the field. To further the identification of knowledge gaps and prioritization of the most effective and feasible measures for reducing plastic emissions and pollution in Norway, the NEA has hosted four expert group workshops since 2017. The first two workshops summarized recent results from short projects financed directly by the NEA, and served to establish a national knowledge base, build scientific capacity, and facilitate cross stakeholder group communication. The workshop in October 2019 specifically addressed the use of microplastic research in Norway as the basis for revising existing Norwegian action plans. In this paper, we review the state-of-the-art of Norwegian microplastic research as it was initiated and gathered by a broad range of Norwegian experts in the NEA workshop in October 2019, covering (1) monitoring, (2) source tracking, (3) processes and fate of microplastic pollution, and (4) hazard characterization and implications. This is presented with a special focus on the Norwegian environment. Through this review, we aim to highlight priority research topics and optimum approaches to facilitate ways forward for microplastic research in Norway and beyond.

2. Monitoring as the basis of knowledge

Environmental monitoring describes the processes and activities that are required to characterize the status of the environment. Monitoring can be divided into two distinct types – compliance and investigative. Compliance is in response to addressing specific requests, often in the form of limits, from governments etc., while investigative monitoring includes research driven sampling campaigns and baselines studies. Monitoring as a tool is a vital component in solving environmental



1972
The Norwegian Ministry of the Environment (Miljøverndepartementet) is established.

1974
Norwegian Pollution Control Authority (Statens forurensingstilsyn) is established.

1976
Environmental tax on beverage packaging enters into force. The government releases a white paper about pollution, establishing the 'polluter pays' principle as a pillar in environmental management. The government aims to tax polluting emissions and products.

1981
The Pollution Act (forurensingsloven) enters into force.

1988
Introduction of new environmental tax on beverage packaging, regulation for beverage packaging and establishment of national deposit rates for beverage containers.

1990
The Ministry of Environment presents a national review on waste minimisation and recycling. The waste hierarchy is established as the governing principle in Norwegian waste policy.

1992
Norway signs the EEA agreement. The first white paper on waste and recycling, which laid the foundations for following waste regulations in Norway, is released. The industry establishes a voluntary extended producer responsibility (EPR) system for plastic packaging.

1993
The Pollution Act is updated to better account for the strategies laid down in the white paper, including establishing the polluter pays principle as a basic principle in Norwegian waste regulation.

2004
The waste regulation (avfallsforskriften) is approved. The regulation contains chapters on different waste fractions, specifying obligations for the waste management industry.

2007
The Water Regulation (vannforskriften) enters into force as the implementation of the European Water Directive in Norwegian law, setting targets for the management of water bodies.

2008
The European Waste framework directive is approved, providing waste management principles such as the polluter pays principle and EPR.

2009
The ban on landfilling of biological waste is adopted in Norway.

2013
The National Waste Strategy is published. Plastic is considered as a key waste stream.

2014
Following a proposal by Norway, the first UNEA passed a resolution that recognised marine litter and microplastics as a global concern.

2015
The Norwegian Grant Scheme for Measures combatting Marine litter is established.

2016
The Norwegian Environment Agency produces the first report on possible national measures for reducing marine litter and microplastics.

2017
Following a proposal by Norway, UNEA-3 agreed to the long term vision of eliminating all discharge of plastic litter into the ocean. The Norwegian government presents a white paper on waste policies in a circular economy with an emphasis on increasing reuse and recycling. The white paper also presents a Plastic Strategy to reduce marine litter. New packaging waste regulations are introduced that implement the Packaging and Packaging Waste (PPW) Directive, including requirements for EPR for plastic packaging. The largest actors in the Norwegian retail/trade sectors agree to meet the national obligations in EU Directive 94/62/EC through the establishment of the Norwegian Retailers' Environment Fund (Handelens Miljøfond). The fund finances initiatives aimed at reducing and preventing plastic pollution.

2018
The Norwegian Aid Programme for Marine Litter is established as a 4 year program.

2019
During the Basel Conference of the Parties, governments amended the Basel Convention to include plastic waste in a legally-binding framework which will make global trade in plastic waste more transparent and better regulated.

2020
The Norwegian Environment Agency updates its recommendation on measures towards reducing marine litter and microplastics. A report is released by the Nordic Council of Ministers calling for a new global agreement to prevent plastic pollution.

2021
National regulations against the use of plastic rubber granulate material on sports fields and banning oxo-degradable plastics from the Norwegian market. Ban on single use plastics brought into force. The Directorate of Fisheries releases an action plan on marine litter from fisheries. The Norwegian Aid Programme for Marine Litter is extended until 2024.

Fig. 1. Timeline of political activities led by Norway for reducing environmental contamination with marine litter and plastics.

challenges. It enables investigation of past conditions, an understanding of the present, and facilitates foreseeing the future. For decades, Norwegian environment authorities have carried out monitoring of nutrient and contaminant levels inland, along the coast and in the open ocean, as well as their effects on biota (e.g., Boitsov et al., 2019; Dietz et al., 2019; Green et al., 2019; Gundersen et al., 2019; Jartun et al., 2019; Letcher et al., 2010; Schartau et al., 2020). Long-term monitoring also makes it possible to evaluate trends and effects in the environment, as well as the impact of mitigation and remediation actions (Fig. 2). Generally, it is essential to have a clearly defined purpose for monitoring, which is then conducted using standardized or quality-assured methods. The same should apply when monitoring microplastic pollution.

Routine, long-term and multi-matrix monitoring programs for microplastic have not yet been implemented in Norway. Early microplastic research, which focused on the occurrence of microplastic and source characterization, served to underline the general lack of data in Norway (Nerland et al., 2014; Sundt et al., 2014; Trevail et al., 2015). Much of this research was exploratory, relied on opportunistic sampling with limited capacity for replication, and employed bespoke methods. For example, researchers identified microplastic in pelagic waters (Lusher et al., 2015), sediments (Woodall et al., 2014) and biota (Bråte et al., 2016; Trevail et al., 2015) along the Norwegian coastline and in the European Arctic. Later research activities focused on establishing baseline datasets (e.g., Bergmann et al., 2017; Cózar et al., 2017; Garmo et al., 2018; Haave et al., 2019; Jensen and Cramer, 2017; Kühn et al., 2018), while simultaneously defining and improving methodologies for sampling, sample processing and analysis (e.g., Haave, 2017; Lusher et al., 2017, 2018; von Friesen et al., 2019), assessing indicators for monitoring (e.g., Bråte et al., 2018a, 2020; Herzke et al., 2016), and quantifying contributions from various sources (e.g., Albretsen et al., 2018; Bauer et al., 2017; Bergmann et al., 2019; Knutsen et al., 2020; Møllhausen et al., 2017; Rødland et al., 2020; Herzke et al., 2021; Yakushev et al., 2021). Several pilot studies have investigated how to include microplastic into ongoing monitoring programs (Bråte et al., 2020; Green et al., 2018; Lusher et al., 2017). The purpose of future national monitoring activities, which have been initiated in 2021, will assess the spatial and temporal changes in microplastic levels in both freshwater and marine environments, with a long-term perspective of assessing the effectiveness of mitigation measures (E. Farmen, NEA, *personal communication*).

There are various international conventions and organizations which require member states to identify the most appropriate monitoring strategies to report on specific environmental indicators. Early monitoring efforts focused largely on plastic pollution in the ‘macro’ range (>25 mm), under the remit of surveying marine litter. These first efforts to record the problem stemmed from reports in the 1960 s and 70 s of plastic debris in the global ocean that entangled or was ingested by marine biota (Ryan, 2015). These studies were intended to survey the amounts of different plastic items in the marine environment and to unpick potential sources or transport mechanisms (e.g., Cundell, 1973; Dixon and Cooke, 1977; Scott, 1972). Since then, macroplastic monitoring has been conducted or planned for by several international organizations or within a total of 19 marine debris action plans across the globe (Table S2; GPML, 2020). To date, much of this work has centered on the development of technical guidelines for undertaking plastic monitoring (Barnardo et al., 2020; Cheshire et al., 2009; GESAMP, 2019; González et al., 2016); however, several international programs for monitoring macroplastic are already implemented and ongoing, including the assessment of common indicators under OSPAR. Table S2 indicates the role of microplastic as an important component in the ‘marine litter’ or ‘plastic’ definition for several international organizations and working groups. Many guidelines for microplastic (or ‘microlitter’) monitoring have been developed by these groups (e.g., Galgani et al., 2013; GESAMP, 2019; Michida et al., 2019) and monitoring surveys have been already undertaken by NOAA, HELCOM, and CPPS. OSPAR has established beach litter items (>2.5 cm) and seafloor litter items as indicators, which has been important for the identification of sources. Similarly, the OSPAR Ecological Quality Objective indicator for plastics (>1 mm) found in the stomach of beached Fulmars (*Fulmarus glacialis)* has now been implemented in the management plans (OSPAR Agreement 2014–01). Yet, no indicators have thus far been implemented for microplastic (Busch, 2016; Trevail et al., 2015). There are currently several expert groups working towards building a consensus on microplastic monitoring, including the use of sediment samples under OSPAR. Within Europe, the EU Marine Strategy Framework Directive (EU MSFD) includes marine litter as a descriptor (#10) for the definition of Good Environmental Status. In contrast, the EU Water Framework Directive (EU WFD) currently contains no quality element for the classification of status related to litter. The Arctic Monitoring and Assessment Program (AMAP) has initiated an expert group which has been working on the development of guidelines and identification of indicators for the Arctic region (AMAP, 2021). The monitoring of multiple environmental matrices is a time-consuming process that must continue to take into consideration novel methodological approaches that emerge within microplastic research in order to improve cost effectiveness and practical relevance in the longer term.

2.1. Selection of matrices for monitoring

There are four primary environmental compartments – water, sediment/soil, air, and biota – within which one can define specific matrices to be targeted for monitoring. For example, surface waters and the water column are the main matrices identified for studying microplastic within seawater or freshwater bodies. Sediments can be differentiated by their environment, such as beaches, coasts, benthic marine sediments, rivers, and lakes. Biota can be categorized by taxonomic group or their ecology (e.g., life history stage, feeding strategy, habitat). The principle reason for defining specific matrices is that they can have vastly different characteristics. Simply referring to a ’water’ or ’sediment’ sample is insufficient to allow for comparisons between investigations. The selection of sample matrices should be based on the aims of the monitoring exercise, with certain matrices likely to be more relevant than others.

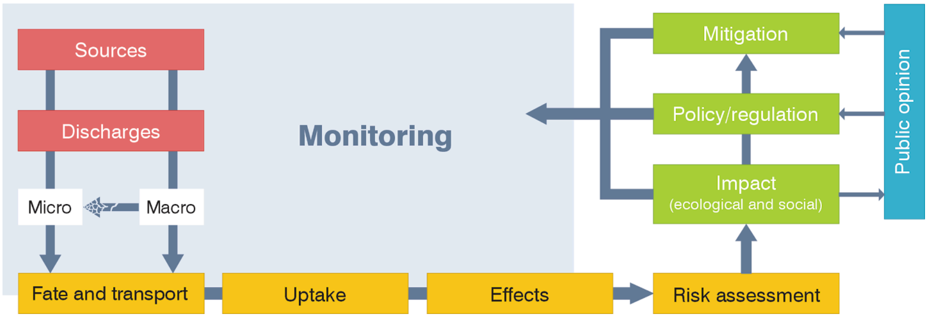


Fig. 2. Conceptual framework showing the role of monitoring in research and regulation related to plastic contamination of the environment.

Factors such as sampling approach and the number of suitable replicates to achieve sufficient statistical power require further investigation (Lusher et al., 2017; Underwood et al., 2017), across all matrices.

Consideration needs to be given to the purpose of monitoring a specific matrix. For example, microplastic in surface waters could be monitored to assess distribution or sources, though there are some challenges to both sampling and interpretation of the results. Large volumes of water are typically needed (>1000 L, Koelmans et al., 2019), more so for offshore waters and the water column, where concentrations are typically lower (Lusher et al., 2014, 2015). The targeted plastic particle size range will influence those needs. Microplastic may be distributed over long distances and are in transition when in the water column. Particles may either have been recently introduced, are buoyant, and therefore transported widely, or have sunk due to higher inherent densities or density changes resulting from biofouling or degradation processes (Booth et al., 2018). Hence, for a simply mapped plastic particle distribution, there may not be a clear link to sources or to impact. Furthermore, biogenic material abundant in productive coastal waters (e.g., phyto- and zooplankton) may complicate sample processing and interpretation of the results.

Sediments have been identified as a sink for microplastic and potentially offer a good basis for monitoring spatial and temporal changes (Booth et al., 2018; Collard et al., 2021; Gomiero et al., 2019a; Haave et al., 2019; Møskeland et al., 2018; Scherer et al., 2020). However, the representativeness of samples will depend on factors such as sedimentation rates, bioturbation, dynamics of thermo-haline and surface currents, as well as other biotic and abiotic variables. Assessing certain sample locations in isolation will not provide a comprehensive overview of microplastic levels. For example, deep-water stations or areas of low bioproduction have lower sedimentation rates which cannot directly be compared to coastal zones. These factors should be collected, reported and acknowledged when interpreting microplastic data.

Biota are regularly used as a matrix in metal and chemical monitoring programs (e.g., Beyer et al., 2017; Oehlmann and Schulte-Oehlmann, 2003; Zhou et al., 2008). Several criteria should be considered when selecting the most appropriate sentinel species. They should be abundant in the environment, easy to sample, commercially or ecologically important, well understood regarding their biology, provide a measurable response reflecting the whole population, community or ecosystem, and be comparable at regional, national, and international scales (Gerhardt, 2002; OSPAR, 2018). Identifying suitable species for biomonitoring programs can be challenging and no single species is relevant across marine, freshwater, and terrestrial ecosystems, or latitudinal gradients. Furthermore, organisms that are internationally accepted for use in monitoring of conventional metal and chemical pollutants may not be optimal for particulate pollutants such as microplastic. Exposure to microplastic for individuals of any species is dependent on several factors, including mobility, feeding mechanism, life stage, organism to particle size ratio, ecological niche, and environmental conditions (Booth and Sørensen, 2020; Halsband and Booth, 2020; Scherer et al., 2018). Furthermore, biota demonstrate a range of particle selectivity and gut retention times which can also be particle specific (Kinjo et al., 2019; Ward et al., 2019). The exposure will also be influenced by heterogenous environmental distributions of microplastic, depending on emission sources, environmental conditions, as well as particle size and polymer type (Haave et al., 2019). Many different species have similar life histories, habitats, and modes of feeding. Hence, monitoring combinations of similar species representing the same habitat and life histories appear to be the best options, if the investigated area cannot be covered by monitoring a single species (Bråte et al., 2020). The use of a range of species will support the comparability between monitoring programs across the globe, especially for ecologically important areas like the high Arctic, which do not harbor species already identified as indicators, such as the blue mussel (*Mytilus* spp.).

An example of a widely available and commonly used bioindicator species in national and international monitoring programs for conventional contaminants is bivalve molluscs (e.g., Beyer et al., 2017; Bråte et al., 2018a, 2020; Gomiero et al., 2019b; Green et al., 2018). As bivalves exhibit particle-specific selectivity (Ward et al., 2019), their use as bioindicators can be advantageous if it is understood which particle types are selected. A recent study assessing benthic bivalves from 100 sites within Nordic countries concluded that blue mussel (*Mytilus* spp.), Baltic macoma (*Limecola balthica)* and *Abra nitida* could be suitable for monitoring microplastic in Nordic waters (Bråte et al., 2020). Other promising candidate bioindicators are fish and benthic polychaetes; however, further studies are needed to assess their potential use in biomonitoring programs targeted for microplastic pollution (Møskeland et al., 2019). One issue with the biomonitoring of microplastic is that targeting particles in digestive tracts represents only a snapshot that can easily over- or underrepresent exposure.

Additional matrices that may be monitored for (micro)plastic include diverse sample types from human systems, such as wastewater treatment (e.g., influent, effluent, sewage sludge), industrial discharges, transportation (e.g., road runoff), urban or indoor dust, drinking water, food products, and human samples (e.g. blood, feces). There has been notable public and media interest in the occurrence of microplastic in food and drink, related to human exposure and perceived risks of negative health effects. Yet, the extent to which this exposure will cause harm is far from being well-understood (Vethaak & Legler, 2021; VKM, 2019). Samples from wastewater treatment plants (WWTPs) and road environments warrant particular attention, due to their potential to represent substantial sources of microplastic to the environment (Kole et al., 2017; Schmidt et al., 2020). Untreated wastewater has been identified as an important pathway through which high microplastic loads enter recipient water bodies (Woodward et al., 2021; Herzke et al., 2021), which is significant given that approximately one fifth of the Norwegian population is not connected to a WWTP, with instead only coarse mechanical removal of debris (SSB, 2017). Monitoring environmental releases from these sources is an important priority, as relatively well-established solutions (e.g., treating wastewater, collecting road runoff) are available to curb these emissions.

2.2. *Incorporation of microplastic into monitoring programs*

As monitoring strategies for microplastic are developed and validated, their incorporation into ongoing monitoring programs with already established sampling sites should be considered. Such ongoing sites represent a variety of potential sources, impacts, and supporting metadata (parameters and time-trends). For example, analyzing microplastic in mussels simultaneously with other contaminants has shown promise in Norway (Bråte et al., 2018a), as has the assessment of sediments collected in parallel to surveys of oil and gas fields on the Norwegian Continental Shelf and through the MAREANO program (Arp et al., 2019; Jensen and Bellec, 2019; Knutsen et al., 2019; Møskeland et al., 2018). Efficient monitoring programs are reliant on harmonized methodologies and data reporting, as well as the availability of dedicated databases with long-term support. However, opportunistic sampling during ongoing activities with no specific microplastic focus should be discouraged, to avoid the contamination of samples due to the use of unsuited equipment and/or untrained personal. Furthermore, experts trained specifically in microplastic sampling should conduct sampling on monitoring campaigns targeting multiple contaminants for most matrices.

For comparison between national and international monitoring programs, protocols for microplastic sampling, sample processing, and analysis must be harmonized and/or standardized and shared openly. No single one-size-fits-all solution or approach exists for all microplastic monitoring endeavors, and thus coordination to facilitate comparisons is important. Guidelines are being developed on an international level and steps to consolidate recommendations have been made through the recent publication of the joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean (GESAMP, 2019) and associated reports under the UN. Norwegian researchers participate in GESAMP, as well as the Working Group on Marine Litter (WGML), Working Group on Marine Sediments (WGMS) and Marine Chemistry Working Group (MCWG) under the International Council for the Exploration of the Sea (ICES), and in working groups under the Arctic Council (AMAP, PAME and CAFF - Conservation of Arctic Flora and Fauna), and OSPAR. These working groups form a network with other national and international advisory bodies, ensuring that results and national experiences are taken into consideration when developing the guidelines. To date, methods for marine matrices including seawater, sediments, seabirds, and bivalves are well developed for plastic particle sizes > 300 μm, while other matrices including air, wastewater effluents, sludge etc. are not. Approaches to analyze the size fraction 50 – 300 μm are currently being optimized. Methods covering particle sizes below 50 μm, however, are still in the research and development stage globally, limiting the availability of reliable data for this size range. Due to the current lack of harmonized and cost-effective methods for identifying and quantifying smaller particles, monitoring programs are most likely to standardize on a lower particle size limit of 300 μm in the shorter term. Further knowledge on the impacts of different microplastic sizes to organisms is expected to influence whether the 300 μm cut-off will need to be revised to include smaller particles in the longer term.

As technology continues to advance, researchers are opting to utilize more (semi-)automated observations within microplastic research, including camera-based solutions, artificial intelligence and image recognition, as well as more advanced instrumentation such as flow cytometry or hyperspectral imaging, etc. (e.g., Cowger et al., 2020; da Silva et al., 2020; Faltynkova et al.; Hufnagl et al., 2019; Primpke et al., 2020; Zhu et al., 2021). These approaches will allow high throughput measurements in the future, decreasing the cost of monitoring efforts. Due to the early stage of method development – especially regarding smaller particle sizes (<300 μm) and complex sample matrices (e.g., soil or wastewater) – the resulting guidelines cannot be static but need to be flexible for future improvements and technological developments.

2.3. *Status of knowledge for microplastics in Norway*

Fig. 3 presents the spatial distribution of sites that have been studied for microplastic occurrence in the Norwegian environment to date. Following the international trend in microplastic research, marine studies far outweigh both freshwater and terrestrial investigations. The maps show the distribution of sites for different environmental matrices.

Biota have been the most strategically studied environmental matrix in the Norwegian environment thus far, representing a range of different species and the greatest spatial coverage. Several coordinated investigations into the occurrence of microplastic in mussels and other bivalves have been undertaken using reproducible methods (Green et al., 2018; Bråte et al., 2018a, 2020). Investigations into polychaetes have focused on testing methodologies and have been limited to offshore and fjord samples (e.g., Bour et al., 2018; Knutsen et al., 2020; Granberg et al., 2020). Benthic amphipods were also investigated in Svalbard

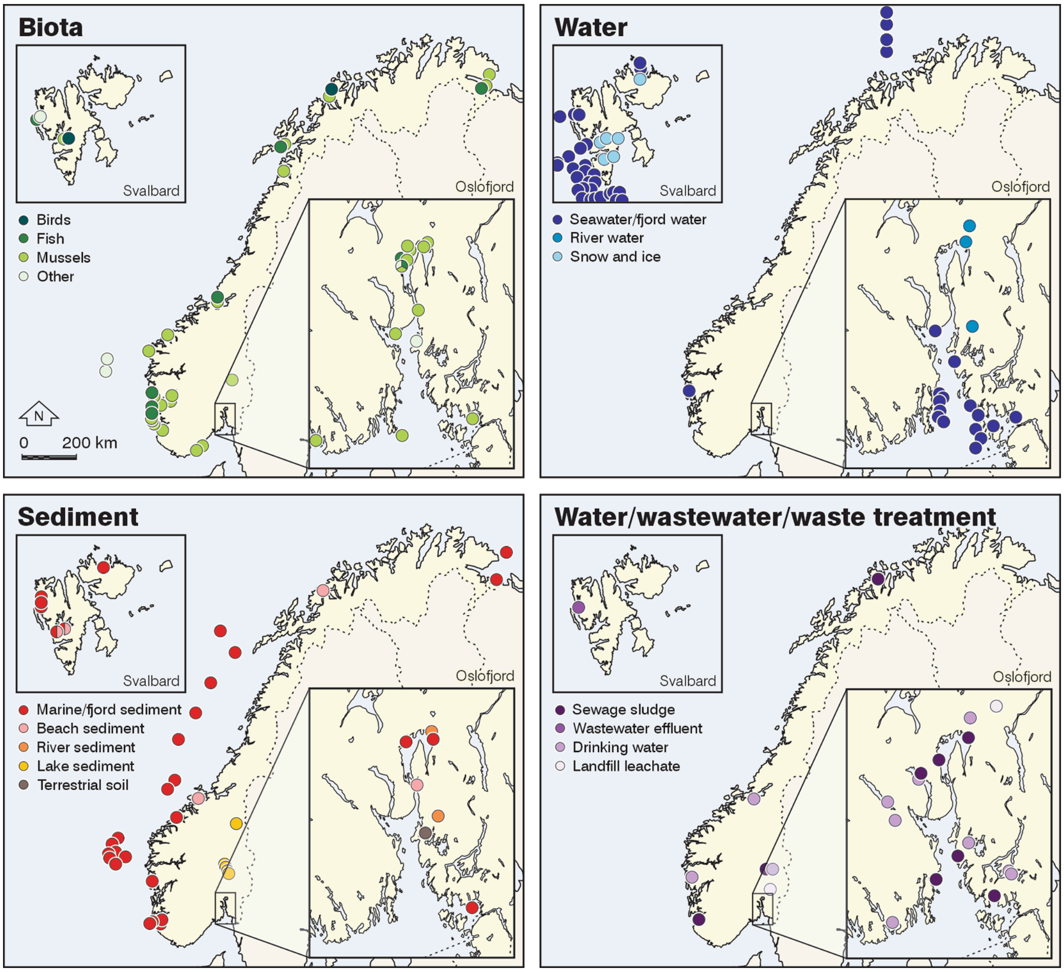


Fig. 3. Sampling locations where microplastic presence has been reported for different sample matrices in Norway and the Norwegian marine environment. "Other" in the Biota map refers to polychaetes and isopods. A full list of the references corresponding to each map is presented in Table S3 of the Supplementary Materials.

(Iannilli et al., 2019). Fish have been investigated for their potential as indicators of plastic pollution, although these investigations have typically focused on larger plastic particles (Bråte et al., 2016) or specifically fibers in the high Arctic (Kühn et al., 2018). Preliminary investigations into smaller particles down to 10 μm in the edible tissues of fish have begun, but the methods require further development and optimization (Gomiero et al., 2020; Haave and Gomiero, 2020). There have only been three studies thus far that have monitored plastics in birds, and these have focused on particles > 1 mm; in alignment with OSPAR guidelines (Trevail et al., 2015) or alongside the monitoring of chemical contaminants (Herzke et al., 2019; Neumann et al., 2021). It is notable, however, that almost all biota monitoring in Norway has been on coastal species. Only a single study has investigated microplastic in a freshwater species (Lusher et al., 2019a).

Fig. 3 clearly highlights an uneven pattern in the distribution of sites so far used for water monitoring. Even though the Norwegian coastline is characterized by a complex system of fjords and coastal waters that are relevant for several commercial activities, very little investigation has taken place in these environments. Instead, most of the sampling of Norwegian waters is contained to the Svalbard coastal environment (e.g., Carlsson et al., 2021; Kanhai et al., 2018; Lusher et al., 2015; von Friesen et al., 2020) and the Oslo fjord (e.g., Albretsen et al., 2018), reflecting a focus on the capital city and the Arctic environment. Outside of this, sampling has taken place in Northern Norway (Lusher et al., 2015) and in the Bergen Fjord (Nerheim and Lusher, 2020). In addition, almost 200 sites have been sampled in the waters around Svalbard and the Barents Sea between mainland Norway and Svalbard, but do not fit within the limits of the map (e.g., Cózar et al., 2017; Kanhai et al., 2018; Tekman et al., 2020). Freshwater investigations are even more limited, with a single study reporting the presence of microplastic in three Norwegian rivers (Lorenz et al., 2020). Recently, snow and ice samples from the Norwegian environment have been investigated for microplastic pollution, but these have been limited to the Svalbard region (Bergmann et al., 2019; Peeken et al., 2018; von Friesen et al., 2020). The majority of these studies aim to report the distribution of microplastic in different aquatic matrices, although some have also assessed the role of point sources, such as WWTPs (Granberg et al., 2019; von Friesen et al., 2020).

Sediment sampling sites, although few in number, are distributed more evenly across the Norwegian environment, including offshore sediments (Møskeland et al., 2018; Knutsen et al., 2020), coastal sediments (Collard et al., 2021; Granberg et al., 2019; Haave et al., 2019; Jensen and Cramer, 2017; Jensen and Bellec, 2019; Olsen et al., 2020), freshwater sediments (Lorenz et al., 2020; Lusher et al., 2019a; Clayer et al., 2021), and soils (Ranneklev et al., 2019). Unfortunately, the diversity of methods applied limit the extent to which the gathered datasets can be compared. The MAREANO program and efforts to monitor contamination around offshore oil and gas platforms account for much of the marine sediment sampling (Møskeland et al., 2019; Knutsen et al., 2019, 2020). These sites are likely to be repeated in future campaigns as they are already utilized for other environmental samples. It is recommended that further sampling of freshwater, terrestrial, and coastal sediments as well as soils is prioritized to assess the spatial and temporal distributions of microplastic pollution in Norway.

In addition to biota, water, and sediment matrices, Norwegian microplastic sampling activities have included drinking water (Gomiero et al., 2021; Uhl et al., 2018), samples from WWTPs (Granberg et al., 2019; Lusher et al., 2018; Skogerbø, 2020), and a small number of landfill leachate samples (van Praagh et al., 2018). Many of these studies have been funded – at least in part – by the Norwegian authorities and specific industries. For example, drinking water was assessed across Norway as part of a nationwide assessment for the Norwegian Water Association (Norsk Vann), including samples of groundwater, processed water, and tap water. This work highlighted that further sampling should address issues associated with sample volumes and background contamination (Gomiero et al., 2021; Uhl et al., 2018). Microplastic has been sampled in sewage sludge from around the country, targeting different population centers (Lusher et al., 2018), as part of a study funded by the NEA. Industry and governance represent important stakeholders in the Norwegian microplastic monitoring landscape, informing study design with their site-specific expertise and funding projects to assess microplastic occurrence. Further monitoring of WWTPs should also consider less densely populated areas that may not employ the same treatment technology as larger population centers.

An important aspect is that a great deal of work has already been conducted related to microplastic sampling in the Norwegian environment (Fig. 3). This includes several studies that address microplastic distribution on a national scale. Yet, there are still data gaps as well as incompatibilities of produced data that persist. Studies on additional important media, such as air and wet and dry deposition, are still ongoing as pilot studies but far from covering a similar geographical area as for the other compartments. Another important component relates to the temporal aspect of monitoring studies. Many markers shown in Fig. 3 relate to isolated studies that sample only a single point in time for each site or station. Only a small number of studies have undertaken repeated sampling to identify changes in microplastic occurrence over time (e.g., Green et al., 2018; Bråte et al., 2018a, 2020). Thus, the role of seasonality in microplastic distributions should also be investigated, in addition to other potential controls, such as meteorological (e.g., storms) and biological phenomena (e.g., algal blooms) on microplastic occurrence across a range of spatial and temporal scales. However, that cannot be undertaken as long as methods are not providing sufficient measured repeatability. A coordinated effort is required to harmonize data that addresses persistent knowledge gaps about microplastic pollution in the Norwegian environment. This should form part of a quality assessment procedure for existing and future monitoring programs to ensure the production of high-quality outputs with wide applicability to a range of end-users.

3. Microplastic sources: Identification, monitoring, and management

Identifying the sources of plastic pollution allows policy makers to design legislative measures to reduce or prevent plastic release. Both the initial source and the environmental release pathway are relevant when discussing sources of microplastic. Many microplastics originate from the direct use or handling of plastic products and are discharged through non-environmental systems (e.g., in wastewater). For example, fibrous microplastic can be generated during the washing of synthetic textiles (Napper and Thompson, 2016). These fibers typically enter the wastewater system before they may ultimately be discharged to the environment (Ben-David et al., 2021; Freeman et al., 2020). The release pathway (e.g., wastewater effluent or sludge application to land) is not the source of the plastic, but it connects the initial source (i.e., synthetic textiles) to the environment. Both components are important when identifying measures to reduce microplastic pollution, that is, reducing the use or generation of microplastic and preventing them from being released to the environment. The involvement of industrial stakeholders in this process is critical. Their contribution to provide information on specific local sources of pollution, the availability and feasibility of alternatives, or the economic consequences of different potential regulatory measures should form part of a balanced assessment of the most suitable actions to control the release of microplastic.

While the initial sources of some larger plastic litter items can be inferred from their morphology (e.g., unique product shapes) or labelling, the measurable properties of microplastic (e.g., shape, color, polymer type) rarely permit the identification of specific source products, producers or polluters. Even where the origin of an item can be established, the mechanisms of environmental release or responsible actors may not be easily deduced. Conversely, knowing the mode of release may not shed light on the initial source of a microplastic particle. Many release mechanisms and pathways (e.g., WWTPs) also involve mixing of particles from different sources before they are discharged into the environment. Thus, tracking the sources and release pathways of microplastic is complex unless very specific particles are identified, or monitoring is done close to potential sources (e.g., Karlsson et al., 2018; Granberg et al., 2019; Mani et al., 2019). Source tracking may not represent the most feasible approach for managing microplastic pollution. Information about the physical and chemical properties may, in rare circumstances, give an indication of the source and means of transport (e.g., Mani et al., 2019), though estimates of microplastic contributions to the environment from various sources need to be based on other approaches, such as material flow analyses (e.g., Kawecki et al., 2018; Frehland et al., 2020).

Sundt et al. (2014) conducted the first characterization of land- and sea-based sources of microplastic in Norway using estimates of emissions and a lifecycle modelling approach. When considering primary microplastic (i.e., particles specifically manufactured within the microplastic size range), the report estimated that about 8,000 metric tons were released annually, which equates to 1.6 kg per capita. The approach adopted for calculating estimates and the data sources used meant that it was not possible to make a similar estimate for secondary microplastics (i.e., those generated through fragmentation during or after use of plastic products). The lack of macroplastic release and subsequent breakdown information was highlighted as a key knowledge gap. The report concluded that it was important to obtain more information across the industrial sector, and it called for industry to take an active part in providing data for future estimations. In 2020, the NEA initiated a comprehensive update of microplastic sources to the Norwegian environment (Lusher and Pettersen, 2021; Sundt et al., 2021), building upon recent attempts to quantify the amount of microplastic released from terrestrial sources, such as from sewage sludge (Lusher et al., 2018), farmland (Ranneklev et al., 2019), and roads (Vogelsang et al. 2019). Microplastic from land-based sources were estimated at 19,000 tons annually (uncertainty range 9,000–30,000; Sundt et al., 2021), whereas values for sea-based sources could not be estimated due to the paucity in available and reliable data (Lusher and Pettersen, 2021).

Based on these estimates, terrestrial sources and release pathways account for a significant proportion of microplastic emissions (Schmidt et al., 2017; Sundt et al., 2014, 2021). Determining the origin of microplastic may be less complicated in some environments, where the impact of local pressures can be more easily delimited and quantified. Moreover, all plastics are produced on land, are predominately used on land, and most landfills and other waste disposal areas are located on land (Hurley et al., 2020). Land-based systems should, therefore, be prioritized when embarking on source tracking work or in legislative measures. Initiation of monitoring programs in freshwater and terrestrial systems will help to establish the magnitude of microplastic pollution and remove the bias in public opinion that currently might exist, tending to place microplastic pollution into marine environments, predominantly. Furthermore, many sources of land-based microplastic emissions are under national control, including industrial sources that may fall under the control of national pollution authorities, for example. This strengthens the case for the management of microplastic for example by mandatory monitoring of microplastic releases (i.e., through industrial discharge or wastewater). Monitoring of such releases – or recipient environments – could help to identify optimal strategies to significantly reduce microplastic emissions and environmental pollution. Effective enactment of this approach will include industry representatives as stakeholders, allowing for open communication and data sharing to identify sources or releases of plastics and appropriate measures for mitigation.

This is further reinforced by the recent proposal by the European Chemicals Agency (ECHA) to restrict intentionally added microplastic in consumer products. The proposal document highlighted soils, particularly those amended with sewage sludge, as an important recipient for microplastics (ECHA, 2019). WWTPs receive microplastics from a diverse array of sources and whilst they are effective in removing particles, these captured microplastics are primarily transferred to the sewage sludge (Ben-David et al., 2021; Freeman et al., 2020; Lusher et al., 2019b; Skogerbø, 2020). Land application of sewage sludge is a common practice for amending the nutrient or chemical quality of soils, but it also leads to the release of microplastic to the environment (Hurley and Nizzetto, 2018; Nizzetto et al., 2016). Once added to soils, microplastic may be transported to connected terrestrial or aquatic environments (Crossman et al., 2020), propagating pollution across wider spatial scales. The recent EU directive on the landfilling of waste (EU2018/850) and the corresponding Norwegian ban on landfilling of organic waste (Fig. 1), may drive an increase in the use of sewage sludge as a soil conditioner. Monitoring of sludge and recipient soils offers the possibility of assessing microplastic emissions and their subsequent transport pathways, forming the basis for establishing approaches to reduce microplastic pollution of the wider environment.

In contrast, identifying, monitoring, and managing microplastic sources in coastal or open waters is more challenging. It is unlikely that all plastic particles recorded in the Norwegian marine environment are derived from Norwegian sources (Booth et al., 2018; MEPEX, 2020). The influence of long-range ocean currents and winds have the potential to transport microplastic from other Scandinavian regions, Europe, or even further afield. To tackle this, it is necessary to develop international policy instruments and rely on the actions of all nations to collectively reduce microplastic releases (Gago et al., 2020; Mæland and Staupe-Delgado, 2020; Tessnow-von Wysocki and Le Billon, 2019). Even after sources are brought under control, the legacy of past plastic pollution is likely to persist in the environment for a long time, especially given that the release of microplastic from terrestrial stores may operate across relatively long timescales (e.g. release from fluvial/lacustrine sedimentary environments such as floodplains or lake sediments) (Hurley et al., 2020).

Within the near future, some improvement in microplastic pollution can be made by focusing on specific sources within the environment. In 2020, the NEA initiated an attempt to quantify the flux of microplastic from ocean-based sources relevant to Norway. Fisheries and aquaculture operations were identified as potential sources, with discharges identified from production, operations, waste treatment, and household. Unfortunately, there is not enough information to provide accurate estimates of release from these sources (Lusher and Pettersen, 2021). For example, fish farms have been identified as a potentially important source of microplastic, although initial investigations highlight the need for further work to fully understand the mechanisms and magnitudes of microplastic release (Gomiero et al., 2020; Johnsen et al., 2019).

While it is difficult to have an impact on external sources of microplastic transported to Norwegian environments, in the shorter-term Norway can focus on tackling and reducing domestic emissions. The generation of high-quality data on microplastic sources and release pathways for policy makers requires research efforts to be focused on effective monitoring; where the local sources can readily be defined, rather than attempting to trace the pathways over long ranges from undetermined sources. A more rigorous assessment of different industry sectors as well as the use and waste handling of plastics in Norway is required. This calls for a more open dialogue with representatives from key stakeholder groups that can provide data on production and usage volumes, along with information on losses and discharges. The recent updates on Norwegian microplastic emission estimates highlight priority industries where data is currently lacking (Lusher and Pettersen, 2021; Sundt et al., 2021). For example, there is no data available on microplastic generated from dredging, decommissioning, abandoned lost and discarded fishing gear (ALDFG), and offshore windfarms. Similarly, there is very limited information related to petroleum and other offshore discharges from maritime traffic. In addition, car tire abrasion has been recognized as the largest contributor within land-based sources (Sundt et al., 2021) and data is urgently required to validate these estimations. Working together with these industries to generate emission values and quantify releases is paramount. Here, the aim can be to reduce emissions as much as possible following the precautionary principle, even before effects thresholds are established. Source inventories for spatially resolved environment units are one measure to improve transparency in the plastics sector. This approach may represent an efficient means of making a significant reduction in microplastic pollution in the environment, as it can utilize frameworks and policy instruments that already exist for other types of contamination.

Internationally, several ongoing projects funded by the Norwegian Ministry of Foreign Affairs and the Norwegian Development Program to Combat Marine Litter and Microplastics are tackling releases of (micro) plastic to the environment – and in particular the ocean – with a focus on Asia and Africa (Table S1). Likewise, the Food and Agriculture Organization of the United Nations (FAO) has been collaborating with the Norwegian Agency for Development Cooperation and the Institute of Marine Research (IMR) through the Dr. Fridtjof Nansen survey program to enable African, Asian and Latin American collaborator nations to build their own fisheries monitoring program which includes microplastic. These aim to build capacity in the Global South, and to establish low-cost methodologies for local actors to undertake monitoring of plastic pollution. This is intended to result in a reduction of plastic emissions from countries highlighted as being amongst the top polluting nations for plastic release to the oceans (e.g. Jambeck et al., 2015; Lebreton et al., 2017). Such efforts, including initiatives from other countries, account for the globality of the plastic pollution problem and will eventually help reducing plastic pollution being “imported” to the Norwegian environment. In the long run, they may also contribute to global governance and producer responsibility, as plastic may be produced in nations which are different from where it is littered, and other groups of people might suffer most from impacts than those that benefit from the use of plastic.

4. Fate: Understanding microplastic transport and degradation processes

Occurrence data provides useful geographic information about the occurrence of microplastics but is less useful for understanding factors governing their distribution and fate. Scientific knowledge about the ageing and degradation processes affecting microplastic exists within the polymer science field, but still needs to be applied to a range of specific and relevant environmental contexts (e.g., Booth and Sørensen, 2020; Halsband and Herzke, 2019; Jahnke et al., 2017). Without a good understanding of the processes of microplastic release, transport, deposition, degradation, and biological interaction, it is not possible to adequately explain contamination hotspots or spatial and temporal patterns. Understanding these processes becomes particularly relevant when working towards mitigation strategies or environmental risk assessments. For example, it is important to understand whether the occurrence of a microplastic hotspot is governed by its proximity to sources (e.g., harbors where hull treatment occurs), a convergence of particles as a result of environmental processes (e.g., oceanic currents or depositional environments), or a combination of these factors.

Some theoretical assumptions regarding microplastic dynamics can be made, and first data corroborating these assumptions are published. For example, the influence of density will impact the buoyancy of particles in aquatic systems, as well as partitioning between water and sediment. Plastic particles with different sizes and morphologies behave differently with respect to entrainment and transport, deposition and sinking rates (Haave et al., 2019; Herzke et al., 2021; Sun et al., 2021), and uptake by organisms. Some environmental processes will impact microplastic distributions, such as tides and currents in the marine environment, and temperature, pH, and redox processes in aquatic systems (Everaert et al., 2018). Research on these processes should center upon two key themes: fundamental processes and environmental modelling (e.g., Alimi et al., 2018; Nizzetto et al., 2016).

Within Norway, advancements have been made regarding the fundamental processes governing microplastic weathering and subsequent aggregation and sedimentation in the coastal environment. National funded projects such as MICROFIBRE and ArcticFibre have demonstrated that UV degradation is a critical process in driving changes in the physicochemical properties of synthetic fibers, including fragmentation, increased surface area, and release of additive chemicals (Sait et al., 2021; Sørensen et al., 2021). These physicochemical changes alter the fate, transport, and potential for interaction with biota. Through the JPI-Oceans funded WEATHER-MIC project, the Norwegian Geotechnical Institute (NGI) conducted lab-scale experiments in conditions relevant to the Oslo fjord (Jahnke, 2019). This also supported an assessment of microplastic in sediments of the Norwegian Continental shelf, whereby the controls on particle sinking rates were addressed (Møskeland et al., 2018). Research on these fundamental processes should continue within Norway and internationally to further elucidate the intrinsic and extrinsic properties of microplastic that govern their distribution in the environment. This must be facilitated not only through basic research to establish the underlying science, but also as a means for generating the new data needed for improving monitoring and modelling work.

Modelling of spatially defined environmental regions, such as river catchments or oceanic current systems, can help to account for some of the environmental complexity, simulate processes that determine the dynamics of microplastic pollution, and predict spatial and temporal patterns. Some modelling work exists internationally (e.g., Everaert et al., 2018, 2020; Mountford and Morales Maqueda, 2019; Sherman and van Sebille, 2016), but thorough calibration and validation of models using robust (specific, quality assured, reproducible) environmental data is still hindered by the lack of appropriate datasets and research into fundamental processes. In the Norwegian context, model development is ongoing. A preliminary study applying Lagrangian modelling to coastal environments indicated seasonal variations in transport barriers influencing the movement of microplastic along the continental shelf, as well as the transport from external waters into the Norwegian coastal environment (Booth et al., 2018). Furthermore, the transport and fate of microplastic fibers was modelled in the Norwegian marine environment which indicated areas around the Norwegian coast where microplastic may accumulate (Booth et al., 2018). Regarding the terrestrial environment, NIVA host an integrated hydrological and sediment catchment model INCA-Microplastic (Nizzetto et al., 2016) and has developed an openly available framework designed to run the model with biogeochemical system data (https://github.com/NIVANorge/Mobius). In addition, Norwegian institutions have good expertise in modelling the coastal and open sea environment for a range of other contaminants (e.g., Eregno et al., 2018; Simonsen et al., 2019). As part of the new JPI-Oceans project FACTS, there are plans to exploit existing models e.g., FLEXPART, to track the transfer of microplastic from land to the sea via atmospheric transport. Results have already revealed high transport efficiencies of road-associated microplastic to remote regions (Evangeliou et al., 2020). It is critical that modelers are involved in the planning of studies to generate empirical data to ensure its usability in the development and optimization of models. Future monitoring programs, in both Norwegian and international contexts, should therefore consider the data requirements for effective modelling of observed results. This includes ensuring meaningful spatial and temporal resolution of collected datasets, as well as the measurement of additional parameters, such as sediment particle size or other relevant environmental processes pertaining to hydrology, geomorphology, and oceanography, for example. Proper development of models is a dynamic process which demands *trans*-disciplinary exchange of needs and constructive criticism amongst stakeholders and end users. This in turn will help construct effective monitoring strategies that produce the most valuable datasets.

5. Importance of understanding the impacts of microplastic

Monitoring programs and effects studies need to be coordinated in order to be mutually beneficial. The impact of microplastic on biota has been high on the international plastics research agenda, and alongside robust exposure data, is necessary for assessing risk. Many studies have now addressed effects of microplastic on organisms, although synthesis of this data to formulate risk assessments is hindered by lack of comparable study parameters (e.g., VKM, 2019). Yet, several studies have compiled such data to assess risk of specific types of microplastics or environments (e.g., Besseling et al., 2019; Burns and Boxall, 2018; Everaert et al., 2018; Wik and Dave, 2009). Microplastics represent a complex, heterogeneous mix of particles with diverse physio-chemical properties (polymers, morphologies, chemical formulation). These present a broad potential for interactions with biota across the physio-biochemical spectrum, representing potential risks and/or benefits from the cellular to the ecosystem level (Galloway et al., 2017; Lambert et al. 2017; Rochman et al. 2019). Microplastic toxicity may depend on a combination of: (1) intrinsic particle properties, including particle size distribution, extent of weathering, morphology and polymer type; (2) exposure conditions such as concentration and exposure time; (3) biological parameters such as species, life stage and feeding mechanism; and (4) toxic chemicals transported by microplastic (mainly additives and their degradation products) (Kögel et al., 2020a,b; Gallo et al., 2018; Wang et al., 2018; Zimmermann et al., 2020). As a result, elucidating the drivers and mechanisms underlying microplastic toxicity remains a significant challenge.

Research into both exposure to and the hazards of microplastics needs to be balanced to enable a high-quality assessment of the environmental risks, yet the current situation does not reflect this need. Microplastics are a complex group of anthropogenic pollutants consisting of particles with different sizes, shapes, polymers, additives and chemical composition (Lambert et al., 2017; Rochman et al., 2019). There is an increasing amount of data on the environmental levels of larger microplastic (>100 μm) that can be used for estimating exposure but might not reflect the distribution of smaller plastic (Haave et al., 2019, Gomiero et al., 2020). Toxicity data crucial to assess the hazard of microplastic is severely underrepresented, even more so in the size range for which most exposure data exist (>100 μm). This situation has led to a marked disconnect between exposure data based on quantifying large microplastic in the environment and toxicity data that usually focuses on smaller microplastics (<100 μm) or nanoplastics (<1 μm). While determining robust environmental concentration data for small microplastics and nanoplastics remains an analytical challenge, comparable size classes and particle types should be used in both exposure and toxicity studies, and not used to extrapolate for other size classes without evidence that that is valid. The potential toxicological effects of nano- and microplastics on biota have been investigated in a growing number of studies from Norway (e.g., Booth et al., 2016; Bour et al., 2018; Bråte et al., 2018b; Capolupo et al., 2020; Cole et al., 2019; Gomes et al., 2020; Halsband et al., 2020; Sørensen et al., 2020) and internationally (e.g., Scherer et al., 2018; Schür et al., 2021; Weber et al., 2021; Zimmermann et al., 2020). Frequently reported and stipulated effects include those from cellular to population levels, such as changes in energy metabolism (e.g., Bour et al., 2018), feeding, growth, movement, stress, immune system effects, hormone regulation, and altered lipid metabolism (reviewed in Kögel et al., 2020a,b), although many gaps remain in the current available research (VKM, 2019). Since studies based on standard ecotoxicological endpoints for assessing chemical exposure (survival, growth, development, reproduction, cell-level effects) have inherent limitations and lack sensitivity, no final conclusions on the toxicity of nano- and microplastics can be made (Barboza et al., 2018; Gomes et al., 2021; Halsband and Booth, 2020; VKM, 2019).

Most toxicity data have been produced using high microplastic concentrations and virgin reference materials (e.g., spherical and lacking the additives and other chemicals associated with microplastic present in the environment), while fragments and fibers seem to dominate in environmental occurrence. Consequently, there is a mismatch between the effects assessed for virgin microplastic under laboratory conditions and the effects of degraded, irregular fragments with a suite of associated chemicals that are found in the environment. For example, small particles appear to induce the biggest effect in the laboratory, but there is insufficient information on the concentrations, aggregation, and bioavailability of such particles in the environment. Furthermore, there is limited knowledge concerning the toxicity of partially degraded or aged plastic materials (e.g., Vroom et al., 2017) and recent research shows that some aged microplastics are less toxic than pristine ones (Schür et al., 2021). The test materials used in many toxicity studies are therefore not particularly indicative of the microplastics that organisms encounter in the environment (Gomes et al., 2021; Halsband and Booth, 2020). This has resulted in a situation where it is difficult to reach precise conclusions over exposure, hazard, and risk.

Recently, the Norwegian Scientific Committee for Food and Environment (VKM) published an opinion on the state of the science of microplastic (VKM, 2019). This contribution was a major step forward in the scientific field, as it critically evaluated research quality with an aim to assess the risk of microplastic to the environment and human health. This assessment highlighted that there is currently insufficient data to draw any conclusions about the impacts of microplastic on human health. More data is available on the environmental toxicity. Of the 122 available effects studies, most focused on the impacts of microplastic on the growth and survival of biota, as well as on the induction of oxidative stress. Ecologically relevant effects on populations and communities have rarely been investigated, whilst understanding microplastic and nanoplastic impacts on species from lower trophic levels that can potentially put a whole ecosystem at risk, also needs more attention (Gomes et al., 2020). Based on the available exposure data, previous risk assessments have concluded that microplastic pose a relatively low risk given our current knowledge on environmental levels (e.g., Adam et al., 2019; Burns and Boxall, 2018; Everaert et al., 2018). VKM used a systematic literature review approach to assess the hazard associated with microplastic based on the latest findings (VKM, 2019). The resulting hazardous concentrations that affect 5% of all species was found to be rather low (HC_5 of 70 particles per liter) and will be easily exceeded in the future or at hotspots. This risk may be further exacerbated as emissions and environmental concentrations increase. In an updated risk assessment of floating microplastic, Everaert et al., (2020) suggested that to date, 0.17% of the global ocean is at risk to microplastic, and under a business-as-usual scenario this increased to 0.52% in 2050 and 1.62% by 2100.

As stated above, the toxicity depends not only on the exposure concentration and duration but also on the physico-chemical properties of microplastics, including size, extent of weathering, morphology and polymer type. It is therefore critical that the research community moves away from viewing microplastics as a single pollutant and starts to consider it as the complex continuum of pollutants that it is (Lambert et al. 2017; Rochman et al. 2019). To comprehensively assess the risk of microplastic, researchers need to establish toxicologically relevant classes of microplastics based on the properties identified as the main drivers of toxicity. The impacts of these classes need to be studied in different species at different developmental stages and trophic levels, and for a range of toxicological endpoints (including chronic exposure). Such assessment should also include representatives of all relevant polymer types in both pristine and partially degraded forms, as well as with particles containing representative contents of additive chemicals.

A more comprehensive overview of cellular and sub-cellular mechanisms is also necessary to complement information provided by endpoints with high ecological relevance (e.g., survival and reproduction), as well as the influence of particle uptake and accumulation on the observed effects. In addition, naturally occurring particles must also be incorporated into effects studies for benchmarking plastic particle toxicity. Furthermore, toxicity data must be interpreted within a broader ecological context as biota are subjected to multiple stressors, including other chemicals, nutritional deficit, and/or climate change. Compiling comprehensive knowledge of the impacts of microplastic in as many species as possible with multiple endpoints is desirable but time consuming.

Importantly, research needs to move from describing toxic effects of particles towards understanding the underlying mechanisms of action and toxicity pathways affected. Here, modelling approaches have a significant role to play with regard to testing mechanistical hypotheses as well as prioritizing endpoints and species to investigate further. Such approaches are well established for chemicals and are currently being developed for particulate pollutants such as nanomaterials (Cao et al., 2020). In addition, model-based approaches can facilitate translation of individual-level effects to populations. A recent study combined dynamic energy budget modelling of loggerhead turtles ingesting plastic at the individual level with population dynamics modelling (Marn et al., 2020). The authors identified ecological breakpoints including negative population growth, for different proportions of plastic in the turtle's digestive systems. Such approaches are not only valuable to predict ecological effects of plastic pollution that are difficult to study experimentally, but also enable projecting the future impacts of plastic debris.

The current lack of comprehensive knowledge and validated models related to plastic impacts should not be used as an argument for postponing political action regarding the need for regulation or cessation of release. A pragmatic approach would be to prioritize the most toxic materials and the most sensitive species based on the available knowledge, support toxicological research to fill the relevant knowledge gaps, and develop predictive modelling tools (Gomes et al., 2021; VKM, 2019).

The capacity of microplastic to act as a vector for chemicals, either compounds included as part of the polymer (e.g., additives) or chemicals that sorb to plastics during or after use (e.g. heavy metals or persistent organic pollutants), is also an important additional aspect of microplastic pollution. Plastic chemicals may influence the toxicity of microplastic (Capolupo et al., 2020; Halsband et al., 2020; Kühn et al., 2020; Sait et al., 2021; Sørensen et al., 2021; Zimmermann et al., 2020), but this is rarely considered within microplastic hazard assessment, especially when reference materials are used. Adsorption of environmental pollutants to microplastic and their subsequent bioavailability to organisms following particle ingestion has also been the focus of an increasing number of studies, for example in seabirds (Herzke et al., 2016, 2019; Neumann et al., 2021). So far, no direct link between chemical concentrations in liver of seabirds and intestinal plastic content could be established. Studies in Norway have attempted to investigate this process under more environmentally relevant scenarios and results have shown negligible impacts (e.g., Herzke et al., 2016, 2019; Sørensen et al., 2020). Of most concern are toxic plastic additives, such as phthalates (Hermabessiere et al., 2017). These should be a focus of future hazard assessments and have started to be implemented in a study investigating microplastic content in salmonids (Gomiero et al., 2020). In general, exposure scenarios for microplastic toxicity studies should differentiate cases where microplastic is the main exposure material vs surrounding water or sediment, and the resulting impact this has on the bioavailability of the additive.

6. Moving forward with priority research

To holistically understand microplastic pollution, multidisciplinary efforts at both national and international levels are essential. Much of the necessary research infrastructure and expertise in Norway is distributed across the country and many collaborative projects have been established in recent years (Table S1). Despite this, current research at the national and international level is to some extent uncoordinated and fragmented, often being governed by the strategic interest of single actors, with limited overarching coordination that would ensure a broad coverage of topics across both natural and social sciences (Crippa et al., 2019; Group of Chief Scientific Advisors, 2019; SAPEA, 2019; Wang et al., 2021). This is partially caused by research funding policies that are highly competitive and favor small, standalone pilot projects, as well as limited national collaboration. While this is important for providing quick answers to policy makers, it cannot provide the fundamental insights needed to address the issue of plastic pollution systemically. As such, large-scale collaborative projects are required to connect national and international expertise and provide a more holistic assessment of microplastic occurrence, fate, and impacts within single studies. Greater interdisciplinarity, particularly regarding connectivity with social and juridical sciences, should be incorporated into future research agendas.

The main approach to prioritizing research is driven by sampling, monitoring activities, or guidelines that are set by governance or policy making organizations. The reason behind this is often to support obligations under national and international regulations and frameworks. Examples of this include the setting of calls for research projects or for standardized methods for monitoring programs. Alternatively, researchers can curate the strategies for generating new knowledge and prioritizing topics for their research. This is done, for example, by submitting proposals for open funding calls. Yet the funding opportunities that allow for this flexibility are less common and typically very competitive.

The confluence of these approaches includes strategies such as the establishment of a global scientific platform on plastic pollution (Group of Chief Scientific Advisors, 2019; Wang et al., 2021), the UNEP Global Partnership on Marine Litter (GPML) Digital Platform, as well as a global observation system (Bank et al. 2021). Norway can support such a platform just like it supports the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Indeed, the Asian Scientific Alliance for Plastic Pollution (ASAP) project is developing an International Knowledge-Hub (IKHAPP) gathering international and local expertise and interests on circular economy, plastic waste management, and pollution controls (Table S1). This could be followed by a corresponding Norwegian initiative to better coordinate and synthesize research at the national level. Irrespective of the approach taken, Norwegian stakeholders, researchers, industry representatives, civil society, and governmental organizations should continue to meet, share and collaborate in order to prioritize research questions and move the field of microplastic pollution forward towards policy development. These key actors have a central role in addressing policy matters related to environmental problems and facilitating research to fill knowledge gaps. Future research should be carefully coordinated and appropriately targeted to answer specific research questions and to generate the knowledge needed by policy makers, requested by society, allowing management of the environment in a sustainable way. Workshops, seminars, and conferences can act as platforms for multiple actors to prioritize future research directions, particularly supporting a two-way bottom-up/top-down communication model. Such an approach was adopted at the NEA workshop on microplastics in October 2019 in Oslo. The output of the discussion on priority research topic has been summarized in Table 1.

In addition to defining future research priorities, these platforms should also be utilized to better engage with the public and provide an opportunity for effective communication of science-based knowledge. There is a disconnect in the way in which results are presented in scientific literature and in the media, and perhaps this has led to a greater perception of the risks potentially posed by microplastic pollution in the public sphere (Völker et al., 2019; Catarino et al., 2021; Soares et al., 2021). The emergence of public opinion opposing microplastic pollution has initiated policy in the absence of significant scientific evidence regarding the important priorities for regulation (Mitrano and Wohlleben, 2020). An example of this is the Microbead Free Waters Act 2015 in the US (Nelson et al., 2019). In some cases, this has diverted the focus from the root of the problem and potential solutions, instead placing

Table 1
Research topics identified as priority during the NEA workshop in October 2019.

Research topic	Reason for prioritization
Degradation and fragmentation of plastics from macro to micro and nano	- Bridge the topic of plastic pollution impacts on the environment and organisms. - Partially degraded microplastics are challenging to characterize and analyze but may be the most environmentally relevant materials for fate and effects studies. - Important for describing the fate and effects of plastics, and to establish regulatory measures.
Quantification methods for low levels and small plastic particles	- Essential to understand environmental distribution and concentrations across all matrices.
Identification of tools and indicators for monitoring	- Baseline (present day) environmental levels must be established at sites selected for long-term monitoring. - Despite the analytical challenges, monitoring efforts should aim at the smaller size fractions, which are currently considered to pose the highest risk. - Enhanced focus on methodological advancements and validation.
Identification of most relevant organisms for monitoring	- Suitability of many species for microplastic monitoring should be tested. - Improved assessment criteria are required. - Candidate organisms should be considered based on their position in the food web, ecological niche, habitats, ecophysiology, geographical distribution, etc. - Using indicator organisms to initiate long term monitoring will allow establishment of baselines and trends.
Quantify environmental distribution and levels	- Baseline (present day) environmental levels must be established in relevant matrices and at sites selected for long-term monitoring.
Microplastic levels in air and atmospheric transportation	- It is necessary to establish the importance of atmospheric transport of microplastic relative to other emission pathways. - Methodology requires validation and optimization with considerations for providing data for atmospheric transport modelling.
Mobilization of microplastic from land (soil) to water	- There is a demand for knowledge regarding the sources of plastic in soils and how the plastic is transported from soils to the aquatic environment.
Dose-response ecotoxicological studies	- Need to understand the risks and implications of relevant and/or high exposures now and in the future.
Impacts of microplastic on biota	- Currently insufficient data regarding the impacts of microplastic on organisms which is preventing meaningful risk assessments. - Information on which species are most sensitive to microplastics is still required. - Assessment of existing ecotoxicity tests and endpoints for use in microplastic studies. - Toxicological investigations should reflect realistic scenarios, including types and levels of microplastic in the environment, as well as exposure times, environmental conditions, exposure to other contaminants, species, developmental stage, and sex. - Complex scenarios, including multiple stressors, as well as naturally occurring particle controls should be addressed. - Implications for biota should be quantified to understand such questions as "what are the safe levels?" and "where does the tolerance lie?" These can be used to define environmental quality standards.
Impacts on human health	- Knowledge of toxicity in relevant animal species and life stages can be used to calculate safety margins and thresholds for safe exposure of humans (tolerable daily intake) through inhalation or ingestion.
Microplastic as a vector for disease	- Role of microplastics in the spreading of bacteria and antibiotic resistance - Attributes related to microplastics that mediate transport
Impact of plastic related chemicals	- A complete database of relevant chemicals is not currently available. - Many additives used in plastic products are known and many have established toxic effects. - The leaching processes into abiotic compartments and their uptake, accumulation and impacts in biota are poorly understood.
Ecosystem approach to risk assessment	- Distributions, weathering, uptake, enrichment, toxicity, transformation, egestion, bioaccumulation and biomagnification patterns should be combined in ecosystem-wide risk assessments and ecological models. - Baselines of environmental levels are required to establish exposure and risk.
Establish relevant regulatory tools	- Regulatory approaches should be harmonized across sectors/authorities. - Regulations must be based on scientific evidence.

potentially undue attention on specific components of the microplastic issue (Kramm et al., 2018; Rist et al., 2018; Backhaus and Wagner, 2020). It may also lead some consumers to change their dietary habits based on false or biased risk assumptions, thereby potentially leading to a lower nutrition quality. Science communications should contextualize scientific findings (Catarino et al., 2021). By communicating science more effectively, there is an opportunity to convert public concern into well-defined and appropriately targeted action. Perceptions on pollution impacts are relevant pro-environmental behaviour predictors (Soares et al., 2021), and public awareness offers the opportunity for a more sustainable plastics economy (Catarino et al., 2021). The public – as heterogeneous as it is – represents an important actor within microplastic research, and future activities should ensure to incorporate their perspectives and tailor outputs and communication accordingly.

7. Conclusions

Emerging global environmental challenges like microplastic pollution require open communication and knowledge sharing to rapidly move towards evidence-based solutions. Fast generation, communication, and dissemination of scientific knowledge is critical but must be balanced with the need for robust study designs, and appropriate quality control and assurance. Frequent and direct dialogue between researchers and policy makers can help authorities navigate towards the robust and simplified scientific knowledge needed as a basis for policy and regulation development. Clear communication of deficiencies in the comparability, quality and reliability of the existing data, which limits its usability, is needed between researchers, policy makers, and other users. While the rapid rise of new digital communication platforms has had a strong and positive effect on media and public engagement in the topic of microplastics, there are significant challenges in safeguarding the quality of knowledge being shared and how it is used further.

Substantial documentation of occurrence and research on microplastic has been undertaken in Norway. This work has begun to establish the spatial and temporal patterns of microplastic pollution in the Norwegian environment, highlight relevant sources, identify important fate and transport processes, and provide an understanding of potential risks. Yet, knowledge gaps remain. In Norway, authorities have taken an active role in seeking robust information that can be used to facilitate identification and prioritization of the most effective and feasible mitigation measures to combat plastic pollution. As a part of this, Norwegian experts in the field of microplastics, industry representatives, and the

Norwegian authorities have shared and discussed latest knowledge to outline the way forward from a Norwegian perspective. The multi-actor concept utilized by Norway – connecting governing bodies, researchers, and stakeholders in open dialogue – represents an ideal approach for efficiently sharing knowledge, identifying priorities for future research, and contributing to the development of policy, regulation, and strategy.

The Norwegian research community is well-positioned as part of the forefront of microplastic research (Table S1 of the Supplementary Material). Through these activities, Norwegian researchers have been involved in many knowledge sharing initiatives and through dissemination and communication actions to stakeholders. The lack of a central strategic platform for research, collaboration, communication, and dissemination is, however, hampering the efficient planning and selection of focus areas for future research. Crucially, appropriate methods for sampling and analysis still need to be developed for several matrices and particle configurations (e.g., different size ranges and degrees of degradation). This development must be accompanied by a process of method validation and harmonization. In parallel, (eco) toxicological approaches must address environmentally relevant scenarios including exposure concentrations, particle morphologies, natural particle composition, and chemical makeup. For a better understanding of toxic effects over time, mechanistic models incorporating consideration of how particles are taken up, distributed and eliminated by different organisms, as well as how adverse effects arise, are required. Importantly, the key question of whether microplastics are more toxic than natural particles must also be addressed. Finally, the ecological consequences of microplastic pollution need to be investigated using whole ecosystem approaches (e.g., mesocosm studies). Closely interlinked communication between all actors is required to facilitate harmonization of strategic research, aiming at avoiding both competitive overlap and gaps, fostering synergistic national collaboration instead of inefficient competition.

CRediT authorship contribution statement

Amy L. Lusher: Conceptualization, Writing - original draft, Writing - review & editing. **Rachel Hurley:** Writing - original draft, Visualization, Writing - review & editing. **Hans Peter H. Arp:** Writing - review & editing. **Andy M. Booth:** Writing - review & editing. **Inger Lise N. Bråte:** Writing - review & editing. **Geir W. Gabrielsen:** Writing - review & editing. **Alessio Gomiero:** Writing - review & editing. **Tânia Gomes:** Writing - review & editing. **Bjørn Einar Grøsvik:** Writing - review & editing. **Norman Green:** Writing - review & editing. **Marte Haave:** Writing - review & editing. **Ingeborg G. Hallanger:** Writing - review & editing. **Claudia Halsband:** Writing - review & editing. **Dorte Herzke:** Writing - review & editing. **Erik J. Joner:** Writing - review & editing. **Tanja Kögel:** Writing - review & editing. **Kirsten Rakkestad:** Writing - review & editing. **Sissel B. Ranneklev:** Writing - review & editing. **Martin Wagner:** Writing - review & editing. **Marianne Olsen:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would thank the Norwegian Environment Agency for supporting the workshop and our colleagues for their valuable feedback during discussions including Claire Coutris, Mihaela Ersvik, Thor Kamfjord, Arne Pettersen, Johanna Skrutvold, Aasmund Vik, Susie Jahren, Janneche Utne Skaare, Morten Jartun, Monica Sanden, Eivind Farmen and Runar Mathisen. We would also like to thank Miriam Mekki in her former role at the Norwegian Environment Agency. AL received funding from the European Union's Horizon 2020 Coordination and Support Action program under grant agreement No 101003805. MW received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 860720. AMB and MW received support from the Research Council of Norway project REVEAL (grant agreement no. 301157). AL, ILNB and TG received support from the Research Council of Norway project MicroLEACH (grant agreement no. 295174).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106794.

References

Adam, V., Yang, T., Nowack, B., 2019. Toward an ecotoxicological risk assessment of microplastic: Comparison of available hazard and exposure data in freshwaters. Environ. Toxicol. Chem. 38 (2), 436–447. https://doi.org/10.1002/etc.4323.

Albretsen, A., Huserbråten, M., Mathisen, H.L., Naustvoll, L.-J., 2018. Marine plastic in the Skagerrak. Rapport fra Havforskningen 28–2018, 25p.

Alimi, O.S., Farner Budarz, J., Hernandez, L.M., Tufenkji, N., 2018. Microplastic and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. 52 (4), 1704–1724. https://doi.org/10.1021/acs.est.7b05559.

AMAP, 2021. Overview of AMAP initiatives for monitoring and assessment of plastic pollution in the Arctic. 4p. https://www.amap.no/documents/download/6714/inline (last accessed 01.07.2021).

Arp, H.P., Laugesen, J., Jensen, T., Knutsen, H., Pettersen, A. Møskeland, T., Huse, J., 2019. Microplastic in sediments on the Norwegian Continental Shelf II: Identification through FT-IR analysis. Norwegian Environment Agency, M-1231, 108p.

Backhaus, T., Wagner, M., 2020. Microplastics in the environment: Much ado about nothing? A debate. Glob. Chall. 4 (6), 1900022. https://doi.org/10.1002/gch2.201900022.

Bank, M.S., Swarzenski, P.W., Duarte, C.M., Rillig, M.C., Koelmans, A.A., Metian, M., Wright, S., Provencher, J.F., Sanden, M., Jordaan, A., Wagner, M., 2021. Global Plastic Pollution Observation System to Aid Policy. Environ. Sci. Technol. 55 (12), 7770–7775. https://doi.org/10.1021/acs.est.1c00818.

Barboza, L.G.A., Frias, J.P.G.L., Booth, A.M., Vieira, L.R., Masura, J., Baker, J., Foster, G., Guilhermino, L., 2018. Microplastic Pollution in the Marine Environment, in: Sheppard, C. (Ed.), World Seas: An Environmental Evaluation, Vol III: Ecological Issues and Environmental Impacts, 2nd edition. Elsevier Science & Technology, 3, pp 329-351.

Barnardo, T., Ribbink, A.J. (Eds), 2020. African Marine Litter Monitoring Manual. Port Elizabeth, South Africa, African Marine Waste Network, Sustainable Seas Trust, 158p. https://doi.org/10.25607/OBP-923.

Bauer, B., Egebæk, K., Aare, A. K., 2017. Environmentally friendly substitute products for rubber granulates as infill for artificial turf fields. Norwegian Environment Agency, M-955, 42p.

Ben-David, E.A., Habibi, M., Haddad, E., Hasanin, M., Angel, D.L., Booth, A.M., Sabbah, I., 2021. Microplastic distributions in a domestic wastewater treatment plant: Removal efficiency, seasonal variation and influence of sampling technique. Sci. Total Environ. 752, 141880 https://doi.org/10.1016/j.scitotenv.2020.141880.

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., Gerdts, G., 2017. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. Environ. Sci. Technol. 51 (19), 11000–11010. https://doi.org/10.1021/acs.est.7b03331.

Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., Gerdts, G., 2019. White and wonderful? Microplastic prevail in snow from the Alps to the Arctic. Sci. Advan. 5 (8), eaax1157. https://doi.org/10.1126/sciadv.aax1157.

Besseling, E., Redondo-Hasselerharm, P., Foekema, E.M., Koelmans, A.A., 2019. Quantifying ecological risks of aquatic micro-and nanoplastic. Crit. Rev. Environ. Sci. Technol. 49 (1), 32–80. https://doi.org/10.1080/10643389.2018.1531688.

Beyer, J., Green, N.W., Brooks, S., Allan, I.J., Ruus, A., Gomes, T., Bråte, I.L.N., Schøyen, M., 2017. Blue mussels (*Mytilus edulis* spp.) as sentinel organisms in coastal pollution monitoring: a review. Mar. Environ. Res. 130, 338–365. https://doi.org/10.1016/j.marenvres.2017.07.024.

Boitsov, S., Grøsvik, B.E., Nesje, G., Malde, K., Klungsøyr, J., 2019. Levels and temporal trends of persistent organic pollutants (POPs) in Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglifinus*) from the southern Barents Sea. Environ. Res. 172, 89–97. https://doi.org/10.1016/j.envres.2019.02.008.

Booth, A.M., Hansen, B.H., Frenzel, M., Johnsen, H., Altin, D., 2016. Uptake and toxicity of methylmethacrylate-based nanoplastic particles in aquatic organisms. Environm. Toxicol. Chem. 35 (7), 1641–1649. https://doi.org/10.1002/etc.3076.

Booth, A.M., Kubowicz, S., Beegle-Krause, C-J., Skancke, J., Nordam, T., Landsem, E., Throne-Holst, M., Jahren, S., 2018. Microplastic in global and Norwegian marine environments: Distributions, degradation mechanisms and transport. Norwegian Environment Agency, M-918, 149p.

Booth, A.M., Sørensen, L., 2020. In: Microplastic Fate and Impacts in the Environment. In: Handbook of Microplastics in the Environment. Springer International Publishing:, Cham, pp. 1–24.

Bour, A., Haarr, A., Keiter, S., Hylland, K., 2018. Environmentally relevant microplastic exposure affects sediment-dwelling bivalves. Environ. Pollut. 236, 652–660. https://doi.org/10.1016/j.envpol.2018.02.006.

Bråte, I.L.N., Eidsvoll, D.P., Steindal, C.C., Thomas, K.V., 2016. Plastic ingestion by Atlantic cod (*Gadus morhua*) from the Norwegian coast. Mar. Pollut. Bull. 112 (1–2), 105–110. https://doi.org/10.1016/j.marpolbul.2016.08.034.

Bråte, I.L.N., Hurley, R., Iversen, K., Beyer, J., Thomas, K.V., Steindal, C.C., Green, N.W., Olsen, M., Lusher, A.L., 2018a. *Mytilus* spp. as sentinels for monitoring microplastic pollution in Norwegian coastal waters: A qualitative and quantitative study. Environ. Pollut. 243, 383–393. https://doi.org/10.1016/j.envpol.2018.08.077.

Bråte, I.L.B., Blázquez, M., Brooks, S.J., Thomas, K.V., 2018b. Weathering impacts the uptake of polyethylene microparticles from toothpaste in Mediterranean mussels (*M. galloprovincialis*). Sci. Tot. Environ. 626 https://doi.org/10.1016/j.scitotenv.2018.01.141.

Bråte, I.L.N., Hurley, R., Lusher, A.L., Buenaventura, N.T., Hultman, M., Halsband, C., Green, N.W., 2020. Microplastic in marine bivalves from the Nordic environment. Nordic Council of Ministers, p. 127, 10.6027/TemaNord2020-504.

Burns, E.E., Boxall, A.B., 2018. Microplastic in the aquatic environment: Evidence for or against adverse impacts and major knowledge gaps. Environ. Toxicol. Chem. 37 (11), 2776–2796. https://doi.org/10.1002/etc.4268.

Busch, K.E.T., 2016. Indikatorer for marin forsøpling – oppsummering fra arbeidsmøte 18.11.2015 (Indicators for marine litter – summary of a workshop 18.11.2015). Norwegian Environment Agency M-456, 19p.

Capolupo, M., Sørensen, L., Jayasena, K.D.R., Booth, A.M., Fabbri, E., 2020. Chemical composition and ecotoxicity of plastic and car tire rubber leachates to aquatic organisms. Water Res. 169, 115270 https://doi.org/10.1016/j.watres.2019.115270.

Carlsson, P., Singdahl-Larsen, C., Lusher, A.L., 2021. Understanding the occurrence and fate of microplastics in coastal Arctic ecosystems: the case of surface waters, sediments and walrus (*Odobenus rosmarus*). Sci. Total Environ. 792, 148308 https://doi.org/10.1016/j.scitotenv.2021.148308.

Cao, J., Pan, Y., Jiang, Y., Qi, R., Yuan, B., Jia, Z., Jiang, J., Wang, Q., 2020. Computer-aided nanotoxicology: risk assessment of metal oxide nanoparticles via nano-QSAR. Green Chem. 22 (11), 3512–3521. https://doi.org/10.1039/D0GC00933D.

Catarino, A.I., Kramm, J., Völker, C., Henry, T.B., Everaert, G., 2021. Risk posed by microplastics: Scientific evidence and public perception. Curr. Opin. Green Sustain. Chem. 29, 100467. https://www.sciencedirect.com/science/article/pii/S2452223621000237.

Cheshire, A., Adler, E., Barbière, J., Cohen, Y., Evans, S., Jarayabhand, S., Jeftic, L., Westphalen, G., 2009. UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter Regional Seas Reports and Studies No. 186 IOC Technical Series No. 83. UNEP Regional Seas Reports and Studies. 131p.

Clayer, F., Jartun, M., Buenaventura, N.T., Guerrero, J.L., Lusher, A., 2021. Bypass of Booming Inputs of Urban and Sludge-Derived Microplastics in a Large Nordic Lake. Environ. Sci. Techno. 55 (12), 7949–7958. https://doi.org/10.1021/acs.est.0c08443.

Cole, M., Coppock, R., Lindeque, P.K., Altin, D., Reed, S., Pond, D.W., Sørensen, L., Galloway, T.S., Booth, A.M., 2019. Effects of nylon microplastic on feeding, lipid accumulation and moulting in a coldwater copepod. Environ. Sci. Technol. 53 (12), 7075–7082. https://doi.org/10.1021/acs.est.9b01853.

Cowger, W., Gray, A., Christiansen, S.H., DeFrond, H., Deshpande, A.D., Hemabessiere, L., Lee, E., Mill, L., Munno, K., Ossmann, B.E., Pittroff, M., Rochman, C., Sarau, G., Tarby, S., Primpke, S., 2020. Critical Review of Processing and Classification Techniques for Images and Spectra in Microplastic Research. Appl. Spectrosc. 74 (9), 989–1010. https://doi.org/10.1177/0003702820929064.

Collard, F., Husum, K., Eppe, G., Malherbe, C., Hallanger, I.G., Divine, D.V., Gabrielsen, G.W., 2021. Anthropogenic particles in sediment from an Arctic fjord. Sci. Total Environ. 772, 145575 https://doi.org/10.1016/j.scitotenv.2021.145575.

Cózar, A., Martí, E., Duarte, C.M., García-de-Lomas, J., Van Sebille, E., Ballatore, T.J., Eguíluz, V.M., González-Gordillo, J.I., Pedrotti, M.L., Echevarría, F., Troublè, R., 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation. Sci. Adv. 3 (4), e1600582 https://doi.org/10.1126/sciadv.1600582.

Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C., Wagner, M., 2019. A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions. M. D. Smet and M. Linder (Eds.). European Commission, Brussels, Belgium. 244p.

Crossman, J., Hurley, R.R., Futter, M., Nizzetto, L., 2020. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. Sci. Total Environ. 724, 138334 https://doi.org/10.1016/j.scitotenv.2020.138334.

Cundell, A.M., 1973. Plastic materials accumulating in Narragansett Bay. Mar. Pollut. Bull. 4 (12), 187–188. https://doi.org/10.1016/0025-326X(73)90226-9.

da Silva, V.H., Murphy, F., Amigo, J.M., Stedmon, C., Strand, J., 2020. Classification and Quantification of Microplastics (<100 μm) Using a Focal Plane Array-Fourier Transform Infrared Imaging System and Machine Learning. Anal. Chem. 92 (20), 13724–13733. https://doi.org/10.1021/acs.analchem.0c01324.

Dixon, T.R., Cooke, A.J., 1977. Discarded containers on a Kent beach. Mar. Pollut. Bull. 8 (5), 105–109. https://doi.org/10.1016/0025-326X(77)90132-1.

Dietz, R., Letcher, R.J., Desforges, J.P., Eulaers, I., Sonne, C., Wilson, S., Andersen-Ranberg, E., Basu, N., Barst, B.D., Bustnes, J.O., Bytingsvik, J., 2019. Current state of knowledge on biological effects from contaminants on arctic wildlife and fish. Sci. Total Environ. 696, 133792 https://doi.org/10.1016/j.scitotenv.2019.133792.

ECHA, 2019. Annex XV Restriction Report. (accessed 21 January 2021). https://echa.europa.eu/documents/10162/12414bc7-6bb2-17e7-c9ec-652a20fa43fc.

Eregno, F.E., Tryland, I., Tjomsland, T., Kempa, M., Heistad, A., 2018. Hydrodynamic modelling of recreational water quality using *Escherichia coli* as an indicator of microbial contamination. J. Hydrol. 561, 179–186. https://doi.org/10.1016/j.jhydrol.2018.04.006.

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., Stohl, A., 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nature Comms. 11 (1), 3381. https://doi.org/10.1038/s41467-020-17201-9.

Everaert, G., Van Cauwenberghe, L., De Rijcke, M., Koelmans, A.A., Mees, J., Vandegehuchte, M., Janssen, C.R., 2018. Risk assessment of microplastic in the ocean: Modelling approach and first conclusions. Environ. Pollut. 242, 1930–1938. https://doi.org/10.1016/j.envpol.2018.07.069.

Everaert, G., De Rijcke, M., Lonneville, B., Janssen, C.R., Backhaus, T., Mees, J., van Sebille, E., Koelmans, A.A., Catarino, A.I., Vandegehuchte, M.B., 2020. Risks of floating microplastic in the global ocean. Environ. Pollut. 267, 115499 https://doi.org/10.1016/j.envpol.2020.115499.

Faltynkova, A., Johnsen, G., Wagner, M. (accepted). Hyperspectral imaging as novel tool to analyze microplastics: Review of the state of the art and recommendations. Microplast. Nanoplast., doi: 10.1186/s43591-021-00014-y.

Freeman, S., Booth, A.M., Sabbah, I., Tiller, R., Dierking, J., Klun, K., Rotter, A., Ben-David, E., Javidpour, J., Angel, D.L., 2020. Between source and sea: The role of wastewater treatment in reducing marine microplastics. J. Environ. Manage. 266, 110642 https://doi.org/10.1016/j.jenvman.2020.110642.

Frehland, S., Kaegi, R., Hufenus, R., Mitrano, D.M., 2020. Long-term assessment of nanoplastic particle and microplastic fiber flux through a pilot wastewater treatment plant using metal-doped plastics. Water Res. 182, 115860 https://doi.org/10.1016/j.watres.2020.115860.

Gago, J., Booth, A.M., Tiller, R., Maes, T., Larreta, J., 2020. In: Microplastics Pollution and Regulation. In: Handbook of Microplastics in the Environment. Springer International Publishing:, Cham, pp. 1–27.

Galgani, F., Hanke, G., Werner, S.D.V.L., De Vrees, L., 2013. Marine litter within the European marine strategy framework directive. ICES J. Mar. Sci. 70 (6), 1055–1064. https://doi.org/10.1093/icesjms/fst122.

Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., Nadal, A., Romano, D., 2018. Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. Environ. Sci. Europe 30 (13), 1–14 https://doi.org/10.1186/s12302-018-0139-z.

Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1, 8. https://doi.org/10.1038/s41559-017-0116.

Garmo, Ø.A., Bråte, I.L.N., Bæk, K., Carlsson, P.M., Grung, M., Lusher, A., 2018. Miljøgiftundersøkelser av ørret fra Akerselva og Lysakerelva i 2018. NIVA-Report 7315–2018, 51p.

GESAMP, 2019. Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean (Kershaw P.J., Turra A. and Galgani F. editors), IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 99, 130p.

Gerhardt, A., 2002. Bioindicator species and their use in biomonitoring. Environmental monitoring I. Encyclopedia of life support systems, UNESCO ed. Eolss, Oxford (UK).

Gomes, T., Almeida, A.C., Georgantzopoulou, A., 2020. Characterization of cell responses in *Rhodomonas baltica* exposed to PMMA nanoplastics. Sci. Total Environ. 726, 138547 https://doi.org/10.1016/j.scitotenv.2020.138547.

Gomes, T., Bour, A., Coutris, A., Almeida, A.C., Bråte, I.G., Wolf, R., Bank, M.S., Lusher, A., 2021. Ecotoxicological impacts of micro- and nanoplastics in terrestrial and aquatic environments. In: Bank, M.S. (Ed.), Microplastic in the Environment: Pattern and Process. Springer Open Press. (In Press), Amsterdam, NL.

Gomiero, A., Øysæd, K.B., Agustsson, T., van Hoytema, N., van Thiel, T., Grati, F., 2019a. First record of characterization, concentration and distribution of microplastic in coastal sediments of an urban fjord in south west Norway using a thermal degradation method. Chemosphere 227, 705–714. https://doi.org/10.1016/j.chemosphere.2019.04.096.

Gomiero, A., Strafella, P., Øysæd, K.B., Fabi, G., 2019b. First occurrence and composition assessment of microplastics in native mussels collected from coastal and offshore areas of the northern and central Adriatic Sea. Environ. Sci. Pollut. Res. 26 (24), 24407–24416. https://doi.org/10.1007/s11356-019-05693-y.

Gomiero, A., Haave, M., Kögel, T., Bjorøy, Ø., Gjessing, M., Berg Lea, T., Horve, E., Martins, C., Olafsen, T., 2020. Tracking of Plastic emissions from aquaculture industry. Report for the fisheries and aquaculture industry research funding- FHF. NORCE Report n. 4 /2020. 71p.

Gomiero, A., Øysæd, K.-B., Palmas, L., Skogerbø, G., 2021. Application of GCMS-pyrolysis to estimate the levels of microplastics in a drinking water supply system. J. Hazard. Mat. 416, 125708 https://doi.org/10.1016/j.jhazmat.2021.125708.

González, D., Hanke, G., Tweehuysen, G., bellert, B., Holzhauer, M., Palatinus, A., Hohenblum, P., Oosterbaan, L., 2016. Riverine Litter Monitoring-Options and Recommendations, MSFD GES TG Marine Litter Thematic Report. Joint Research Centre (JRC), p. 52. https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/MSFD_riverine_litter_monitoring.pdf.

GPML, 2020. Global Partnership on Marine Litter: Action Plans. https://www.gpmarinelitter.org/what-we-do/action-plans (Accessed: 31 July 2020).

Granberg, M., von Friesen, L.W., Bach, L., Collard, F., Gabrielsen, G.W., Strand, J., 2019. Anthropogenic microlitter in wastewater and marine samples from Ny-Ålesund, Barentsburg and Signehamna, Svalbard. Norwegian Environment Agency, C-373, 28p.

Granberg, M., Winberg von Friesen, L., Ask, A., Collard, F., Magnusson, K., Eriksson Wiklund, A.K., Murphy, F., Strand, J., Wing Gabrielsen, G., Bach, L., 2020. Microlitter in arctic marine benthic food chains and potential effects on sediment dwelling fauna. TemaNord 2020 (528), 77p.

Green, N.W., Schøyen, M., Hjermann, D., Øxnevad, S., Ruus, A., Allan, I., Lusher, A., Beylich, B., Lund, E., Tveiten, L., Håvardstun, J., Jenssen, M.T.S., Ribeiro, A.L., Bæk, K., 2018. Contaminants in coastal waters of Norway -2017. Miljøgifter i kystområdene 2017. Norwegian Environment Agency, M-1120, 230p.

Green, N.W., Schøyen, M., Hjermann, D., Øxnevad, S., Ruus, A., Beylich, B., Lund, E., Tveiten, L., Håvardstun, J., Jenssen, M.T.S., Ribeiro, A.L., Doyer, I., Rundberget, T., Bæk, K., 2019. Contaminants in coastal waters of Norway -2018. Norwegian Environment Agency, M-1515, 237p.

Group of Chief Scientific Advisors, 2019. Environmental and health risks of microplastic pollution. European Commission, Brussel, Belgium. 64p. https://op.europa.eu/en/publication-detail/-/publication/f235d1e3-7c4d-11e9-9f05-01aa75ed71a1/language-en/format-PDF/source-108645429. (accessed 21 January 2021).

Gundersen, C.B., Kaste, Ø., Sample, J., Braaten, H. F. V., Selvik, J. R., Hjermann, D. Ø., Norling, M. D., Calidonio, J-L. G., 2019. The Norwegian river monitoring programme – water quality status and trends in 2018 Elveovervåkningsprogrammet – vannkvalitetsstatus og -trender 2018. Norwegian Environment Agency, M-1509, 94p.

Haave, M. 2017. Preliminær undersøkelse av mikroplast i sandfang. UNI-Research Report for Bergen Kommune Vann- og avløpsetaten. 12p.

Haave, M., Lorenz, C., Primpke, S., Gerdts, G., 2019. Different stories told by small and large microplastic in sediment-first report of microplastic concentrations in an urban recipient in Norway. Mar. Pollut. Bull. 141, 501–513. https://doi.org/10.1016/j.marpolbul.2019.02.015.

Haave, M., Gomiero, A., 2020. Mikroplastforurensing i laksefilet og oppdrettsmiljø - Screening av mikroplast i prosesser og ferdig produkt fra lakseoppdrett. NORCE Rapport 2–2020.

Halsband, C., Herzke, D., 2019. Plastic litter in the European Arctic: What do we know? Emerging Contam. 5, 308–318. https://doi.org/10.1016/j.emcon.2019.11.001.

Halsband, C., Booth, A.M., 2020. Ecological impacts of particulate plastics in marine ecosystems. In: Bolan, N. (Ed.), Particulate Plastics in Terrestrial and Aquatic Environments. CRC Press, Boca Raton, USA, pp. 233–248.

Halsband, C., Sørensen, L., Booth, A.M., Herzke, D., 2020. Car tire crumb rubber: Does leaching produce a toxic chemical cocktail in coastal marine systems? Front. Environ. Sci. 8 (125), 00125. https://doi.org/10.3389/fenvs.2020.00125.

Hermabessiere, L., Dehaut, A., Paul-Pont, I., Lacroix, C., Jezequel, R., Soudant, P., Duflos, G., 2017. Occurrence and effects of plastic additives on marine environments and organisms: A review. Chemosphere 182, 781–793. https://doi.org/10.1016/j.chemosphere.2017.05.096.

Herzke, D., Anker-Nilssen, T., Nøst, T.H., Götsch, A., Christensen-Dalsgaard, S., Langset, M., Fangel, K., Koelmans, A.A., 2016. Negligible impact of ingested microplastic on tissue concentrations of persistent organic pollutants in northern fulmars off coastal Norway. Enviro. Sci. Technol. 50 (4), 1924–1933. https://doi.org/10.1021/acs.est.5b04663.

Herzke, D., Rostkowski, P., Harju, M., Borgen, A.R., Christensen-Dalsgaard, S., 2019. Assessment of additives used in plastic in seabirds. NILU report 1/2019. 16pp.

Herzke, D., Ghaffari, P., Sundet, J.H., Tranang, C.A., Halsband, C., 2021. Microplastic Fiber Emissions From Wastewater Effluents: Abundance, Transport Behavior and Exposure Risk for Biota in an Arctic Fjord. Front. Environ. Sci. 9, 194. https://doi.org/10.3389/fenvs.2021.662168.

Hufnagl, B., Steiner, D., Renner, E., Löder, M.G.J., Laforsch, C., Lohninger, H., 2019. A methodology for the fast identification and monitoring of microplastics in environmental samples using random decision forest classifiers. Anal. Methods 11 (17), 2277–2285. https://doi.org/10.1039/C9AY00252A.

Hurley, R.R., Nizzetto, L., 2018. Fate and occurrence of micro (nano) plastics in soils: Knowledge gaps and possible risks. Curr. Opin. Environ. Sci. Health. 1, 6–11. https://doi.org/10.1016/j.coesh.2017.10.006.

Hurley, R., Horton, A., Lusher, A., Nizzetto, L., 2020. Plastic waste in the terrestrial environment, in: Letcher, T.M. (Ed), Plastic Waste and Recycling Academic Press, pp. 163-193.

Iannilli, V., Pasquali, V., Setini, A., Corami, F., 2019. First evidence of microplastics ingestion in benthic amphipods from Svalbard. Environ. Res. 179, 108811 https://doi.org/10.1016/j.envres.2019.108811.

Jahnke, A., 2019. Project Final report: WEATHER-MIC – How microplastic weathering changes its transport, fate and toxicity in the marine environment." JPI. Oceans. 28p.

Jahnke, A., Arp, H.P.H., Escher, B.I., Gewert, B., Gorokhova, E., Kühnel, D., Ogonowski, M., Potthoff, A., Rummel, C., Schmitt-Jansen, M., Toorman, E., 2017. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. Environ. Sci. Technol. Lett. 4 (3), 85–90. https://doi.org/10.1021/acs.estlett.7b00008.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 13, 768–771. https://doi.org/10.1126/science.1260352.

Jartun, M., Økelsrud, A., Rundberget, T., Enge, E. K., Rostkowski, P., Warner, N., Harju, M., Johansen, I., 2019. Monitoring of environmental contaminants in freshwater ecosystems 2018 – Occurrence and biomagnification. Norwegian Environment Agency, M-1411, 85p.

Jensen, H.K.B., Cramer, J., 2017. MAREANOs pilotprosjekt på mikroplast - resultater og forslag til videre arbeid. NGU Rapport nr 2017 (043), 51p.

Jensen, H.K.B., Bellec, V., 2019. Miljøkjemiske data og dateringsresultater fra indre Kongsfjorden og indre Rijpfjorden samt områdene SK01 og SK02 vest for Svalbard – MAREANO. NGU Rapport nr 2019 (027), 294p.

Johnsen, H.R., Haarr, M.L., Roland, A.O., Johannessen, E.R., Bye-Larsen, I., Vagelsten, B. V., Nogueira, L.A., 2019. Sluttrapport HAVPLAST – Marin plast fra norsk sjømatnæring – kartlegging, kvantifisering og handling. SALT rapport nr 1040, 41p.

Kanhai, L.D.K., Gårdfeldt, K., Lyashevska, O., Hassellöv, M., Thompson, R.C., O'Connor, I., 2018. Microplastics in sub-surface waters of the Arctic Central Basin. Mar. Pollut. Bull. 130, 8–18. https://doi.org/10.1016/j.marpolbul.2018.03.011.

Karlsson, T.M., Arneborg, L., Broström, G., Almroth, B.C., Gipperth, L., Hassellöv, M., 2018. The unaccountability case of plastic pellet pollution. Mar. Pollut. Bull. 129 (1), 52–60. https://doi.org/10.1016/j.marpolbul.2018.01.041.

Kawecki, D., Scheeder, P.R., Nowack, B., 2018. Probabilistic material flow analysis of seven commodity plastics in Europe. Environ. Sci. Technol. 52 (17), 9874–9888. https://doi.org/10.1021/acs.est.9b02900.

Kinjo, A., Mizukawa, K., Takada, H., Inoue, K., 2019. Size-dependent elimination of ingested microplastic in the Mediterranean mussel *Mytilus galloprovincialis*. Mar. Pollut. Bull. 149, 110512 https://doi.org/10.1016/j.marpolbul.2019.110512.

Koelmans, A.A., Nor, N.H.M., Hermsen, E., Kooi, M., Mintenig, S.M., De France, J., 2019. Microplastic in freshwaters and drinking water: Critical review and assessment of data quality. Water Res. 155, 410–422. https://doi.org/10.1016/j.watres.2019.02.054.

Kole, P.J., Löhr, A.J., Van Belleghem, F.G.A.J., Ragas, M.J., 2017. Wear and Tear of Tyres: A Stealthy Source of Microplastics in the Environment. Int. J. Environ. Res. Public Health 14 (10), 1265. https://doi.org/10.3390/ijerph14101265.

Kögel, T., Refosco, A., Maage, A., 2020a. In: Surveillance of Seafood for Microplastics. Handbook of Microplastics in the Environment. Springer International Publishing:, Cham, pp. 1–34.

Kögel, T., Bjorøy, Ø., Toto, B., Bienfait, A.M., Sanden, M., 2020b. Micro-and nanoplastic toxicity on aquatic life: Determining factors. Sci. Total Environ. 709, 136050 https://doi.org/10.1016/j.scitotenv.2019.136050.

Kühn, S., Schaafsma, F.L., van Werven, B., Flores, H., Bergmann, M., Egelkraut-Holtus, M., Tekman, M.B., van Franeker, J.A., 2018. Plastic ingestion by juvenile polar cod (*Boreogadus saida*) in the Arctic Ocean. Polar Biol. 41 (6), 1269–1278. https://doi.org/10.1007/s00300-018-2283-8.

Kühn, S., Booth, A.M., Sørensen, L., van Oyen, A., van Franeker, J.A., 2020. Transfer of additive chemicals from marine plastic debris to the stomach oil of northern fulmars. Front. Environ. Sci. 8 (138), 1–14. https://doi.org/10.3389/fenvs.2020.00138.

Knutsen, H., Singdahl-Larsen, C., Cyvin, J.B., Arp, H.P., 2019. Microplastics in Svalbard fjords and Bjørnøy transect Sediments. Norwegian Geotech. Inst. 51, 20190263–01-R.

Knutsen, H., Cyvin, J.B., Totland, C., Lilleeng, Ø., Wade, E.J., Castro, V., Pettersen, A., Laugesen, J., Møskeland, T., Arp, H.P.H., 2020. Microplastic accumulation by tube-dwelling, suspension feeding polychaetes from the sediment surface: A case study from the Norwegian Continental Shelf. Mar. Environ. Res. 161, 105073 https://doi.org/10.1016/j.marenvres.2020.105073.

Kramm, J., Völker, C., Wagner, M., 2018. Superficial or substantial: Why care about microplastics in the anthropocene? Environ. Sci. Technol. 52 (6), 3336–3337. https://pubs.acs.org/doi/10.1021/acs.est.8b00790.

Lambert, S., Scherer, C., Wagner, M., 2017. Ecotoxicity testing of microplastics: Considering the heterogeneity of physicochemical properties. Integr. Environ. Assess. Manage. 13 (3), 470–475. https://doi.org/10.1002/ieam.1901.

Lebreton, L.C.M., van der Zwat, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611. https://doi.org/10.1038/ncomms15611.

Letcher, R.J., Bustnes, J.O., Dietz, R., Jenssen, B.M., Jørgensen, E.H., Sonne, C., Verreault, J., Vijayan, M.M., Gabrielsen, G.W., 2010. Exposure and effects assessment of persistent organohalogen contaminants in arctic wildlife and fish. Sci. Total Environ. 408 (15), 2995–3043. https://doi.org/10.1016/j.scitotenv.2009.10.038.

Lorenz, C., Dolven, J.K., Værøy, N., Stephansen, D., Olsen, S.B., Vollertsen, J. 2020. Microplastic pollution in three rivers in south eastern Norway. Norwegian Environment Agency, M-1572, 54p.

Lusher, A.L., Pettersen, R., 2021. Sea-based sources of microplastics to the Norwegian marine environment. Norwegian Environment Agency, in press.

Lusher, A.L., Burke, A., O'Connor, I., Officer, R., 2014. Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. Mar. Pollut. Bull. 88 (1–2), 325–333. https://doi.org/10.1016/j.marpolbul.2014.08.023.

Lusher, A.L., Tirelli, V., O'Connor, I., Officer, R., 2015. Microplastic in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Rep. 5, 14947. https://doi.org/10.1038/srep14947.

Lusher, A., Bråte, I.L.N., Hurley, R., Iversen, K., Olsen, M., 2017. Testing of methodology for measuring microplastic in blue mussels (Mytilus spp) and sediments, and recommendations for future monitoring of microplastic (R & D-project). Norwegian Environment Agency, M-897, 87p.

Lusher, A.L., Hurley, R., Vogelsang, C., Nizzetto, L., Olsen, M., 2018. Mapping microplastic in sludge. Norwegian Environment Agency, M-907, 57p.

Lusher, A., Buenaventura, N. T., Eidsvoll, D. P., Thrane, J-E., Økelsrud, A., Jartun, M., 2019a. Freshwater microplastic in Norway: A first look at sediment, biota and historical plankton samples from Lake Mjøsa and Lake Femunden. Norwegian Environment Agency, M-1212, 46p.

Lusher, A.L., Hurley, R.R., Vogelsang, C. 2019b. Microplastics in sewage sludge: Captured but released, in: H.K. Karapanagioti and I.K. Kalavrouziotis (Eds.), Microplastics in Water and Wastewater IWA Publishing, pp. 85-100.

Mani, T., Blarer, P., Storck, F.R., Pittroff, M., Wernicke, T., Burkhardt-Holm, P., 2019. Repeated detection of polystyrene microbeads in the lower Rhine River. Environ. Pollut. 245, 634–641. https://doi.org/10.1016/j.envpol.2018.11.036.

Marn, N., Jusup, M., Kooijman, S.A.L.M., Klanjscek, T., 2020. Quantifying impacts of plastic debris on marine wildlife identifies ecological breakpoints. Ecol. Lett. 23 (10), 1479–1487. https://doi.org/10.1111/ele.13574.

MEPEX 2020. A deep dive into our plastic ocean. Report. 5 p. https://mepex.no/wp-content/uploads/2020/03/Mepex_sluttrapport.pdf (accessed 21 January 2021.

Michida, Y., Chavanich, S., Chiba, S., Cordova, M.R., Cozsar Cabanas, A., Glagani, F., Hagmann, P., Hinata, H., Isobe, A., Kershaw, P., Kozlovskii, N., Lusher, A.L. and Martí, E., 2019. Guidelines for Harmonizing Ocean Surface Microplastic Monitoring Methods. Version 1.1. https://doi.org/10.25607/OBP-867.

Mitrano, D., Wohlleben, W., 2020. Microplastic regulation should be more precise to incentivize both innovation and environmental safety. Nat. Commun. 11, 5324. https://doi.org/10.1038/s41467-020-19069-1.

Mountford, A.S., Morales Maqueda, M.A., 2019. Eulerian Modeling of the Three-Dimensional Distribution of Seven Popular Microplastic Types in the Global Ocean. J. Geophys. Res. Oceans 124 (12), 8558–8573. https://doi.org/10.1029/2019JC015050.

Mæland, C.E., Staupe-Delgado, R., 2020. Can the Global Problem of Marine Litter Be Considered a Crisis? Risk Haz. Crisis Public Policy 11 (1), 87–104. https://doi.org/10.1002/rhc3.12180.

Møllhausen, M., Thorsheim, F., Herzke, D., 2017. Rapport fra undersøkelser om svinn av gummigranulat fra kunstgressbaner, gjennomført av over 12 000 elever og spillere høsten 2017. Report for Forskningskampanjen, 19p.

Møskeland, T., Laugesen, J., Jensen, T., Knutsen, H., Arp, H.P., Lilling, Ø., Pettersen, A., 2018. Microplastic in sediments on the Norwegian Continental Shelf. Norwegian Environment Agency, M-976, 84p.

Møskeland, T., Laugesen, J., Jensen, T., Knutsen, H., Arp, H.P., Cyvin, J.B., Pettersen, A., 2019. Microplastic in polychaetes from the Norwegian Continental Shelf. Norwegian Environment Agency, M-1222, 33p.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. Mar. Pollut. Bull. 112 (1–2), 39–45. https://doi.org/10.1016/j.marpolbul.2016.09.025.

Nelson, D., Sellers, K., Mackenzie, S., Weinberg, N., 2019. Microbeads—a Case Study in How Public Outrage Fueled the Emergence of New Regulations. Curr. Pollution Rep. 5, 172–179. https://doi.org/10.1007/s40726-019-00114-7.

Nerheim, M.S., Lusher, A.L., 2020. Investigating microsized anthropogenic particles in Norwegian fjords using opportunistic nondisruptive sampling. Anthropocene Coasts 3 (1), 76–85. https://doi.org/10.1139/anc-2020-0002.

Nerland, I.L., Halsband, C., Allan, I., Thomas, K.V., 2014. Microplastic in marine environments: Occurrence, distribution and effects. Norwegian Environment Agency, M-319, 71p.

Neumann, S., Harju, M., Herzke, D., Anker-Nilssen, T., Christensen-Dalsgaard, S., Langset, M., Gabrielsen, G.W., 2021. Ingested plastics in northern fulmars (*Fulmarus glacialis*): a pathway for polybrominated diphenyl ether (PBDE) exposure? Sci. Total Environ. 788, 146313 https://doi.org/10.1016/j.scitotenv.2021.146313.

Nizzetto, L., Butterfield, D., Futter, M., Lin, Y., Allan, I., Larssen, T., 2016. Assessment of contaminant fate in catchments using a novel integrated hydrobiogeochemical-multimedia fate model. Sci. Total Environ. 544, 553–563. https://doi.org/10.1016/j.scitotenv.2015.11.087.

Oehlmann, J., Schulte-Oehlmann, U., 2003. Molluscs as bioindicators. In: Markert, B.A., Breure, A.M., Zechmeister, H.G. (Eds.), Trace Metals and other Contaminants in the Environment, Vol. 6. Elsevier, pp. 577–635.

OSPAR, 2018. CEMP Guidelines for Monitoring Contaminants in Biota (OSPAR Agreement 1999-02, Revised 2018).

Olsen, L.M.B., Knutsen, H., Mahat, S., Wade, E.J., Arp, H.P.H., 2020. Facilitating microplastic quantification through the introduction of a cellulose dissolution step prior to oxidation: Proof-of-concept and demonstration using diverse samples from the Inner Oslofjord. Norway. Mar. Environ. Res. 161, 105080 https://doi.org/10.1016/j.marenvres.2020.105080.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. 9 (1), 1–12. https://doi.org/10.1038/s41467-018-03825-5.

van Praagh, M., Hartman, C., Brandmyr, E., 2018. Microplastics in landfill leachates in the Nordic Countries. Nordic Council of Ministers, TemaNord, p. 53.

Primpke, S., Christiansen, S.H., Cowger, W., De Frond, H., Deshpande, A., Fischer, M., Holland, E.B., Meyns, M., O'Donnell, B.A., Ossmann, B.E., Pittroff, M., Sarau, G., Scholz-Bottcher, B.M., Wiggin, K.J., 2020. Critical Assessment of Analytical Methods for the Harmonized and Cost-Efficient Analysis of Microplastics. Appl. Spectrosc. 74 (9), 1012–1047. https://doi.org/10.1177/0003702820921465.

Qin, F., Du, J., Gao, J., Liu, G., Song, Y., Yang, A., Wang, H., Ding, Y., Wang, Q., 2020. Bibliometric Profile of Global Microplastics Research from 2004 to 2019. Int. J. Environ. Res. Public Health 17 (16), 5639. https://doi.org/10.3390/ijerph17165639.

Ranneklev, S.B., Hurley, R., Bråte, I.L.N., Vogelsang, C., 2019. Plast i landbruket: kilder, massebalanse og spredning til lokale vannforekomster (Plastland). Norsk Institutt for Vannforskning. ISBN 978-82-577-7153-9. NIVA Rapport 7418-2019, 45p.

Regjeringen, Norwegian Government, 2020. The Norwegian Development Programme to Combat Marine Litter and Microplastic. https://www.regjeringen.no/en/dokumenter/marine_litter/id2642037/ (last accessed 26 January 2021).

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

Rochman, C.M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., Athey, S., Huntington, A., McIlwraith, H., Munno, K., De Frond, H., 2019. Rethinking microplastic as a diverse contaminant suite. Environ. Toxicol. Chem. 38 (4), 703–711. https://doi.org/10.1002/etc.4371.

Ryan, P.G., 2015. A brief history of marine litter research, in: Bergmann, M., Gutow, L., Klages, M., Marine Anthropogenic Litter. Springer, Cham. pp. 1-25.

Rødland, E.S., Okoffo, E.D., Rauert, C., Heier, L.S., Lind, O.C., Reid, M., Thomas, K.V., Meland, S., 2020. Road de-icing salt: Assessment of a potential new source and pathway of microplastics particles from roads. Sci. Total Environ. 738, 139352 https://doi.org/10.1016/j.scitotenv.2020.139352.

Sait, S.T.L., Sørensen, L., Kubowicz, S., Vike-Jonas, K., Gonzalez, S., Asimakopoulos, A. G., Booth, A.M., 2021. Microplastic fibres from synthetic textiles: Environmental degradation and additive chemical content. Environ. Pollut. 268, 115745 https://doi.org/10.1016/j.envpol.2020.115745.

SAPEA, Science Advice for Policy by European Academies, 2019. A Scientific Perspective on Microplastics in Nature and Society. Berlin: SAPEA. https://doi.org/10.26356/microplastics.

Scherer, C., Weber, A., Lambert, S., Wagner, M., 2018. Interactions of Microplastic with Freshwater Biota. In: Wagner, M., Lamber, S. (Eds.), Freshwater Microplastics. Springer, pp. 153–180.

Scherer, C., Weber, A., Stock, F., Vurusic, S., Egerci, H., Kochleus, C., Arendt, N., Foeldi, D., Dierkes, G., Wagner, M., Brennholt, N., Reifferscheid, G., 2020. Comparative assessment of microplastics in water and sediment of a large European river. Sci. Total Environ. 738, 139866 https://doi.org/10.1016/j.scitotenv.2020.139866.

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by rivers into the sea. Environ. Sci. Technol. 51, 12246–12253. https://doi.org/10.1021/acs.est.7b02368.

Schmidt, C., Kumar, R., Yang, S., Büttner, O., 2020. Microplastic particle emission from wastewater treatment plant effluents into river networks in Germany: Loads, spatial patterns of concentrations and potential toxicity. Sci. Total Environ. 737, 139544 https://doi.org/10.1016/j.scitotenv.2020.139544.

Schür, C., Weil, C., Baum, M., Wallraff, J., Schreier, M., Oehlmann, J., Wagner, M., 2021. Incubation in wastewater reduces the multigenerational effects of microplastics in *Daphnia magna*. Environ. Sci. Technol. 55 (4), 2491–2499. https://doi.org/10.1021/acs.est.0c07911.

Schartau, A.K., Birkeland, I.B., Demars, B., H., Hesthagen, T., Hobæk, A., Jensen, T.C., Jenssen, M.T.S., Mjelde, M., Saksgård, R., Skjelbred, B., Velle, G., Walseng. B., 2020. ØKOFERSK – delprogram Vest: Basisovervåking av utvalgte innsjøer i 2019. Overvåking og klassifisering av økologisk tilstand. Norwegian Environment Agency, M-1722, 65p.

Scott, P.G., 1972. Plastics packaging and coastal pollution. Int. J. Environ. Stud. 3 (1–4), 35–36. https://doi.org/10.1080/00207237208709489.

Sherman, P., Van Sebille, E., 2016. Modeling marine surface microplastic transport to assess optimal removal locations. Environ. Res. Lett. 11 (1), 014006 https://doi.org/10.1088/1748-9326/11/1/014006.

Simonsen, M., Lind, O.C., Saetra, Ø., Isachsen, P.E., Teien, H.C., Albretsen, J., Salbu, B., 2019. Coastal transport of river-discharged radionuclides: Impact of speciation and transformation processes in numerical model simulations. Sci. Total Environ. 669, 856–871. https://doi.org/10.1016/j.scitotenv.2019.01.434.

Skogerbø, G., 2020. Mikroplast i avløpsvann, avløpsslam og jord. Norsk Vann Report, 253/2020.

Soares, J., Miguel, I., Venâncio, C., Lopes, I., Oliveira, M., 2021. Public views on plastic pollution: Knowledge, perceived impacts, and pro-environmental behaviours. J. Hazard. Mat. 412, 125227. https://www.sciencedirect.com/science/article/pii/S0304389421001904.

SSB, 2017. Wastewater statistics 'mapped out'. https://www.ssb.no/en/natur-og-miljo/artikler-og-publikasjoner/wastewater-statistics-mapped-out.

Sun, X., Wang, T., Chen, B., Booth, A.M., Liu, S., Wang, R., Zhu, L., Zhao, X., Qu, K., Xia, B., 2021. Factors influencing the occurrence and distribution of microplastics in coastal sediments: From source to sink. J. Hazard. Mat. 410, 124982 https://doi.org/10.1016/j.jhazmat.2020.124982.

Sundt, P., Schulze, P.-E., Syversen, F., 2014. Source of microplastic pollution to the marine environment. Norwegian Environment Agency M-321, 103p.

Sundt et al., 2021. Norsk land baserte kilder til mikroplast. Norwegian Environment Agency Report in Press.

Sørensen, L., Rogers, E., Altin, D., Salaberria, I., Booth, A.M., 2020. Sorption of PAHs to microplastic and their bioavailability and toxicity to marine copepods under co-exposure conditions. Environ. Pollut. 258, 113844 https://doi.org/10.1016/j.envpol.2019.113844.

Sørensen, L., Groven, A.S., Hovsbakken, I.A., Del Puerto, O., Krause, D.K., Sarno, A., Booth, A.M., 2021. UV degradation of natural and synthetic microfibers causes fragmentation and release of polymer degradation products and chemical additives. Sci. Total Environ. 755, 143170 https://doi.org/10.1016/j.scitotenv.2020.143170.

Tekman, M.B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., Bergmann, M., 2020. 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. 54 (7), 4079–4090. https://doi.org/10.1021/acs.est.9b06981.

Tessnow-von Wysocki, I., Le Billon, P., 2019. Plastics at sea: Treaty design for a global solution to marine plastic pollution. Environ. Sci. Policy. 100, 94–104 https://doi.org/10.1016/j.envsci.2019.06.005.

Trevail, A.M., Gabrielsen, G.W., Kühn, S., van Franeker, J.A., 2015. Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (*Fulmarus glacialis*). Polar Bio. 38 (7), 975–981. https://doi.org/10.1007/s00300-015-1657-4.

Uhl, W., Eftekhardadkhah, M., Svendsen, C., 2018. Mapping microplastics in Norwegian drinking water. Norsk Vann report 241 (2018), 43p.

Underwood, A.J., Chapman, M.G., Browne, M.A., 2017. Some problems and practicalities in design and interpretation of samples of microplastic waste. Anal. Methods 9 (9), 1332–1345. https://doi.org/10.1039/C6AY02641A.

Vethaak, A.D., Legler, J., 2021. Microplastics and human health. Science 371 (6530), 672–674. https://doi.org/10.1126/science.abe5041.

VKM, 2019. Microplastic; occurrence, levels and implications for environment and human health related to food. Scientific opinion of the Scientific Steering Committee of the Norwegian Scientific Committee for Food and Environment. VKM report 2019:

16, ISBN: 978-82-8259-332-8, ISSN: 2535-4019. Norwegian Scientific Committee for Food and Environment (VKM), Oslo, Norway. 175p.

Vogelsang, C., Lusher, A.L., Dadkhah, M.E., Sundvor, I., Umar, M., Ranneklev, S.B., Eidsvoll, D., Meland, S., 2019. Microplastic in road dust–characteristics, pathways and measures. Norwegian Environment Agency M-959, 170p.

von Friesen, L.W., Granberg, M.E., Hassellöv, M., Gabrielsen, G.W., 2019. An efficient and gentle digestion protocol for extraction of microplastic from bivalve tissue. Mar. Pollut. Bull. 142, 129–134. https://doi.org/10.1016/j.marpolbul.2019.03.016.

von Friesen, L.W., Granberg, M.E., Pavlova, O., Magnusson, K., Hassellöv, M., Gabrielsen, G.W., 2020. Summer sea ice melt and wastewater are important local sources of microlitter to Svalbard waters. Environ. Int. 139, 105511 https://doi.org/10.1016/j.envint.2020.105511.

Vroom, R.J., Koelmans, A.A., Besseling, E., Halsband, C., 2017. Aging of microplastic promotes their ingestion by marine zooplankton. Environ. Pollut. 231, 987–996. https://doi.org/10.1016/j.envpol.2017.08.088.

Völker, C., Kramm, J., Wanger, M., 2019. On the Creation of Risk: Framing of Microplastics Risks in Science and Media. Glob Chall. 4 (6), 1900010. https://doi.org/10.1002/gch2.201900010.

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

Wang, Z., Altenburger, R., Backhaus, T., Covaci, A., Diamond, M.L., Grimalt, J.O., Lohmann, R., Schäffer, A., Scheringer, M., Selin, H., Soehl, A., 2021. We need a global science-policy body on chemicals and waste. Science 371 (6531), 774–776. https://doi.org/10.1126/science.abe9090.

Ward, J.E., Zhao, S., Holohan, B.A., Mladinich, K.M., Griffin, T.W., Wozniak, J., Shumway, S.E., 2019. 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. 53 (15), 8776–8784. https://doi.org/10.1021/acs.est.9b02073.

Weber, A., von Randow, M., Voigt, A.L., von der Au, M., Fischer, E., Meermann, B., Wagner, M., 2021. Ingestion and toxicity of microplastics in the freshwater gastropod *Lymnaea stagnalis*: No microplastic-induced effects alone or in combination with copper. Chemosphere 263, 128040. https://doi.org/10.1016/j.chemosphere.2020.128040.

Wik, A., Dave, G., 2009. Occurrence and effects of tire wear particles in the environment–A critical review and an initial risk assessment. Environ. Pollut. 157 (1), 1–11. https://doi.org/10.1016/j.envpol.2008.09.028.

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. R. Soc. Open Sci. 1 (4), 140317 https://doi.org/10.1098/rsos.140317.

Woodward, J., Li, J., Rothwell, J., Hurley, R. 2021. Acute riverine microplastic contamination due to avoidable releases of untreated wastewater. Nat. Sustain. https://doi.org/10.1038/s41893-021-00718-2.

Yakushev, E., Gebruk, A., Osadchiev, A., Pakhomova, S., Lusher, A., Berezina, A., van Bavel, B., Vorozheikina, E., Chernykh, D., Kolbasova, G., Razgon, I., 2021. Microplastics distribution in the Eurasian Arctic is affected by Atlantic waters and Siberian rivers. Commun. Earth Environ. 2 (1), 23. https://doi.org/10.1038/s43247-021-00091-0.

Zhang, Y., Pu, S., Lv, X., Gao, Y., Ge, L., 2020. Global trends and prospects in microplastics research: A bibliometric analysis. J. Hazard. Mater. 400, 123110 https://doi.org/10.1016/j.jhazmat.2020.123110.

Zhou, Q., Zhang, J., Fu, J., Shi, J., Jiang, G., 2008. Biomonitoring: an appealing tool for assessment of metal pollution in the aquatic ecosystem. Anal. Chim. Acta 606 (2), 135–150. https://doi.org/10.1016/j.aca.2007.11.018.

Zhu, Y., Yeung, C.H., Lam, E.Y., 2021. Microplastic pollution monitoring with holographic classification and deep learning. J. Phys. Photonics 3 (2), 024013. https://doi.org/10.1088/2515-7647/abf250.

Zimmermann, L., Göttlich, S., Oehlmann, J., Wagner, M., Völker, C., 2020. What are the drivers of microplastic toxicity? Comparing the toxicity of plastic chemicals and particles to *Daphnia magna*. Environ. Pollut. 267, 15392. https://doi.org/10.1016/j.envpol.2020.115392.